APPARATUS AND METHOD FOR JOINT MEASUREMENTS OF CONJUGATED QUADRATURES OF FIELDS OF REFLECTED/SCATTERED AND TRANSMITTED BEAMS BY AN OBJECT IN INTERFEROMETRY

5

This application claims the benefit of U.S. Provisional Application No. 60/442,858, filed January 27, 2003 (ZI-47); and U.S. Provisional Application No. 60/442,892, filed January 28, 2003 (ZI-45), both of which are incorporated herein by reference.

10   This application also incorporates by reference: U.S. Patent Application entitled "Interferometric Confocal Microscopy Incorporating A Pinhole Array Beam-Splitter," filed on January 27, 2004 (ZI-45).

Technical Field

15   This invention relates to the measurement of conjugated quadratures of fields of reflected, scattered and transmitted beams by an object in interferometry.

Background Of The Invention

Over the years people have developed various sophisticated confocal

20   interferometric techniques. Examples of the variety of the available technologies are the following.

There is interferometric, confocal far-field and near-field microscopy using heterodyne techniques and a detector having a single detector element or having a relatively small number of detector elements.

25   There is also interferometric confocal far-field and near-field microscopy using a step and stare method with a single-homodyne detection method for acquiring conjugated quadratures of fields of reflected and/or scattered beams when a detector is used that includes a large number of detector elements. The respective conjugated quadrature of a field is $|a|\sin\phi$ when the quadrature $x(\phi)$ of a field is

30   expressed as $|a|\cos\phi$. The step and stare method and single-homodyne detection method have been used in order to obtain for each detector element a set of at least four electrical interference signal values with a substrate that is stationary with

respect to the respective interferometric microscope during the stare portion of the step and stare method. The set of at least four electrical interference signal values are required to obtain for each detector element conjugated quadratures of fields of a measurement beam comprising a reflected and/or scattered far-field or near-field

5   from a spot in or on a substrate that is conjugate to the each detector element.

There are heterodyne and single-homodyne detection methods to obtain phase information in linear and angular displacement interferometers.

And there is a double homodyne detection method based on use of four detectors wherein each detector generates an electrical interference signal value

10   used to determine a corresponding component of a conjugated quadratures of a field such as described in Section IV of the article by G. M D'ariano and M G. A. Paris entitled "Lower Bounds On Phase Sensitivity In Ideal And Feasible Measurements," *Phys. Rev. A* **49**, 3022-3036 (1994).). The four detectors generate the four electrical interference signal values simultaneously and each electrical interference

15   signal value contains information relevant to one conjugated quadratures component.

High speed, high resolution imaging with high signal-to-noise ratios is required, for example, in inspection of masks and wafers in microlithography. Two techniques that have been used for obtaining high resolution imaging with high

20   signal-to-noise ratios are interferometric far-field and near-field confocal microscopy of the types described above. However, the acquisition of high signal-to-noise ratios with the high resolution imaging generally limits data rates in part by the necessity to acquire conjugated quadratures of fields of a reflected and/or scattered beam for each spot in and/on a substrate being imaged. The determination

25   of conjugated quadratures requires the measurement of at least four electrical interference signal values for the each spots in and/or on the substrate being imaged. Acquisition of the at least four interference signal values for the each spots places tight restrictions on how large a rate of scan can be employed in generation of a one-dimensional, a two-dimensional or three-dimensional image of the substrate

30   having artifacts down to of the order of 100 nm in size or smaller.

Summary of the Invention

The bi-homodyne and quad-homodyne detection methods described herein relax the tight restrictions and permit significantly increased throughput in high resolution imaging that has high signal-to-noise ratios for each spot being imaged.

5   The tight restrictions are relaxed as a consequence of a joint measurement of conjugated quadratures of fields using a conjugate set of four pixels for each spot being imaged wherein the temporal window function for the measured four electrical interference signal values used in the determination of one component of conjugated quadratures of fields is the same as the temporal window function for the

10   measured four interference signal values used in the determination of the second component of the conjugated quadratures of the fields, *i.e.*, the two sets of four interference signal values are the same.

With the bi-homodyne detection method, the two temporal window functions are made the same by using one frequency component of an input beam for the

15   determination of one component of the conjugated quadratures of the fields and using a second frequency component of the input beam for the determination of the second component of the conjugated quadratures of the fields. The two frequency components of the input beam are coextensive in spatial and temporal coordinates, *i.e.*, coextensive in space and have the same temporal window functions in the

20   interferometer system.

With the quad-homodyne detection method, the two temporal window functions are made the same by using two frequency components of an input beam for the determination of one component of the conjugated quadratures of the fields and using two other frequency components of the input beam for the determination

25   of the second component of the conjugated quadratures of the fields. The four frequency components of the input beam are coextensive in spatial and temporal coordinates, *i.e.*, coextensive in space and have the same temporal window functions in the interferometer system.

At least some of the bi-homodyne and quad-homodyne detection methods

30   described herein obtain four electrical interference signal values wherein each

3

measured value of an electrical interference signal contains simultaneously information about two orthogonal components of a conjugated quadratures.

The bi-homodyne detection method uses a single detector element for each electrical interference signal value obtained and an input beam to an interferometer system comprising two frequency components with a frequency difference large compared to the frequency bandwidth of the detector for a joint measurement of the conjugated quadratures. One frequency component is used to generate an electrical interference signal component corresponding to a first component of conjugated quadratures of a field of a corresponding measurement beam comprising either a reflected and/or scattered or transmitted far-field or near-field from a spot in or on a measurement object that is conjugate to the detector element. The second frequency component is used to generate a second electrical interference signal component corresponding to a respective second component of the conjugated quadratures of the field. Information about the first and second components of the conjugated quadratures are obtained jointly as a consequence of the two frequency components being coextensive in space and having the same temporal window function in the interferometer system. The temporal window function when operating in a scanning mode corresponds to the window function of a respective set of pulses of the input beam to the interferometer system.

When operating in the scanning mode and using either the bi-homodyne or quad-homodyne detection methods described herein, conjugate sets of detector elements are defined and used. A conjugate set of detector elements comprises the pixels of the detector conjugate to the spot on or in the substrate at the times that the measurements are made of a corresponding set of the four electrical interference signal values.

For each of the two frequency components of the input beam used in the bi-homodyne detection method, reference and measurement beams are generated. In certain of the embodiments that use the bi-homodyne detection method, different phase shift combinations are introduced between the respective reference and measurement beam components by shifting the frequencies of one or both of the two frequency components for acquiring a set of four electrical interference signal

values for each spot in or on the measurement object that is imaged. In certain other of the embodiments that use the bi-homodyne detection method, different phase shift combinations are introduced between the respective reference and measurement beam components by a phase-shifter for each of the two frequency

5   components for acquiring a set of the four electrical interference signal values for each spot in and/or on a measurement object or substrate that is imaged. In the certain of the embodiments, the difference in optical path of the reference and measurement beams is a non-zero value.

The quad-homodyne detection method uses two detectors and an input beam

10   to an interferometer system comprising four coextensive measurement beams and corresponding reference beams in the interferometer system simultaneously to obtain four electrical signal values wherein each measured value of an electrical interference signal contains simultaneously information about two orthogonal components of a conjugated quadratures for a joint measurement of conjugated

15   quadratures of a field of a beam either reflected and/or scattered or transmitted by a spot on or in a substrate. One detector element is used to obtain two electrical interference signal values and the second detector element is used to obtain two other of the four electrical interference signal values. The four coextensive measurement beams and corresponding reference beams are generated in the

20   interferometer system simultaneously by using an input beam that comprises four frequency components wherein each frequency component corresponds to a measurement and corresponding reference beam. The frequency differences of the four frequency components are such that the four frequency components are resolved by an analyzer into two beams incident on the two different detector

25   elements wherein each of the two beams comprises two different frequency components and the frequency differences are large compared to the frequency bandwidth of the detector. One of the two frequency components incident on a first detector element is used to generate an electrical interference signal component corresponding to a first component of conjugated quadratures of a field of a

30   corresponding measurement beam comprising either a reflected and/or scattered or transmitted far-field or near-field from a spot in or on a measurement object that is

5

conjugate to a detector element. The second of the two frequency components incident on the first detector element is used to generate a second electrical interference signal component corresponding to a respective second component of the conjugated quadratures of the field. The description for the second detector

5   element with respect to frequency components and components of conjugated quadratures is the same as the corresponding description with respect to the first detector element. Information about the first and second components of the conjugated quadratures are accordingly obtained jointly as a consequence of the four frequency components being coextensive in space and having the same

10   temporal window function in the interferometer system. The temporal window function when operating in a scanning mode corresponds to the window function of a respective set of two pulses or pulse sequences of the input beam to the interferometer system.

In general, according to one aspect of the invention, in interferometric far-

15   field and near-field confocal and non-confocal microscopy respective at least four electrical interference signal values are acquired when operating in a relatively fast scanning mode wherein each of the at least four electrical interference signal values correspond to the same respective spot on or in a substrate and contain information that can be used for determination of joint measurements of conjugated quadratures

20   of fields in both spatial and temporal coordinates.

In general, according to another aspect of the invention, joint measurements are made of conjugated quadratures of fields of beams reflected from a measurement object in single or multiple-wavelength linear and angular displacement interferometers.

25   In general, according to still another aspect of the invention, scanning interferometric far-field and near-field confocal and non-confocal microscopy, employing either a bi-homodyne or a quad-homodyne detection method, is used to obtain joint measurements of conjugated quadratures of fields either reflected and/or scattered or transmitted by a substrate with a detector having a large number of

30   detector elements. For each spot in and/or on the substrate that is imaged, a corresponding set of four electrical interference signal values is obtained. Each of

6

the set of four electrical interference signal values contains information for determination of a joint measurement of respective conjugated quadratures of fields.

In general, according to yet another aspect of the invention, in linear and angular displacement interferometry, joint measurements are made of conjugated

5   quadratures of fields of beams reflected from a measurement object.

In general, in one aspect, the invention features an interferometery system for making interferometric measurements of an object. The system includes a beam generation module which during operation delivers an output beam that includes a first beam at a first frequency and a second beam at a second frequency that is different from

10   said first frequency, wherein the first and second beams within the output beam being coextensive, and the beam generation module included a beam conditioner which during operation introduces a sequence of different shifts in a selected parameter of each of the first and second beams, the selected parameter selected from a group consisting of phase and frequency. The system also includes a detector assembly having a detector element,

15   and an interferometer constructed to receive the output beam at least a part of which represents a first measurement beam at the first frequency and a second measurement beam at the second frequency, said interferometer further constructed to image both the first and second measurement beams onto a selected spot on the object to produce therefrom corresponding first and second return measurement beams, and to then

20   simultaneously image the first and second return measurement beams onto said detector element.

Other embodiments include one or more of the following features. The beam generation module further includes a beam source which during operation generates a single input beam at a predetermined frequency, and the beam conditioner includes an

25   optical element that derives the first and second beams from the single input beam. The optical element is an acousto-optic modulator. Each of the first and second beams includes a first component and a second component that is orthogonal to the first component, and the beam conditioner is constructed to introduce a first sequence of different discrete phase shifts into a relative phase difference between the first and second

30   components of the first beam and concurrently therewith a second sequence of different

7

discrete phase shifts into the relative phase difference between the first and second components of the second beam.

In some embodiments, the beam conditioner includes a first phase shifter for introducing the first sequence of different discrete phase shifts into the relative phase
5   difference between the first and second components of the first beam and a second phase shifter for introducing the second sequence of different discrete phase shifts into the relative phase difference between the first and second components of the second beam. In at least some of those cases, the interferometer is characterized by a measurement beam optical path length and a reference beam optical path length and wherein the
10   difference between those two optical path lengths is nominally zero. Also, the interferometer is constructed to generate the first measurement beam from the first component of the first beam and the second measurement beam from the first component of the second beam. And the interferometer is further constructed to generate a first reference beam from the second component of the first beam and a second reference
15   beam from the second component of the second beam. The first phase shifter introduces the first sequence of different discrete phase shifts into the second component of the first beam and the second phase shifter introduces the second sequence of different discrete phase shifts into the second component of the second beam.

In other embodiments, the beam conditioner is constructed to introduce a first
20   sequence of different frequency shifts into the frequency of the first beam and concurrently therewith a second sequence of different frequency shifts into the frequency of the second beam. The beam conditioner includes a first set of acousto-optic modulators for introducing the first sequence of different frequency shifts into the frequency of the first beam and a second set of acousto-optic modulators for introducing
25   the second sequence of different frequency shifts into the frequency of the second beam. In at least some of those cases, the interferometer is characterized by a measurement beam optical path length and a reference beam optical path length and wherein the difference between those two optical path lengths is nominally a non-zero value.

In addition, in other embodiments, the interferometer system further includes a
30   controller which controls the beam conditioner and causes the beam conditioner to introduce the first and second sequences of different shifts in the selected parameter of

each of the first and second beams. The controller is programmed to acquire from the detector assembly measured values for a set of interference signals resulting from introducing the first and second sequences of different shifts in the selected parameters of each of the first and second beams and further programmed to compute first and second

5   components of conjugated quadratures of the fields of beams from said selected spot. The detector element is characterized by a frequency bandwidth and the first and second frequencies are separated by an amount that is larger than the frequency bandwidth of the detector.

The interferometer can be any one of a wide variety of types of interferometer,

10   including without limitation, a scanning interferometric far-field confocal microsope, a scanning interferometric far-field non-confocal microsope, a scanning interferometric near-field confocal microsope, a scanning interferometric near-field non-confocal microsope, and a linear displacement interferometer.

In general, in another aspect, the invention features an interferometery system for

15   making interferometric measurements of an object. The system includes a beam generation module which during operation delivers an output beam that includes a first beam at a first frequency and a second beam at a second frequency that is different from the first frequency, and the first and second beams within the output beam being coextensive. The interferometry system also includes a detector assembly having a

20   detector element that is characterized by a frequency bandwidth, wherein the first and second frequencies are separated by an amount that is larger than the frequency bandwidth of the detector; and an interferometer constructed to receive the output beam, at least a part of which represents within the interferometer a first measurement beam at the first frequency and a second measurement beam at the second frequency. The

25   interferometer is further constructed to simultaneously image both the first and second ⤴ measurement beams onto a selected spot on or in the object to produce therefrom corresponding first and second return measurement beams, and then to simultaneously image the first and second return measurement beams onto the detector element.

In general, in still another aspect, the invention features a source beam assembly

30   including a beam generation module which during operation delivers an output beam that includes a first beam at a first frequency and a second beam at a second frequency that is

different from the first frequency, and wherein the first and second beams within the output beam are coextensive. The beam generation module included a beam conditioner which during operation introduces a sequence of different shifts in a selected parameter of each of the first and second beams, wherein the selected parameter selected from a

5   group consisting of phase and frequency.

In general, in still yet another aspect, the invention features a method of performing measurements of an object using an interferometer. The method includes generating an input beam for the interferometer, wherein the input beam includes a first beam at a first frequency and a second beam at a second frequency that is different from

10   the first frequency, and wherein the first and second beams are coextensive and share the same temporal window. The method further includes, using the interferometer and the input beam supplied to the interferometer, to jointly measure two orthogonal components of conjugated quadratures of fields of reflected, scattered, or transmitted beams from a selected spot in and/or on the object.

15   In general, another aspect, the invention features a method of performing measurements of an object using an interferometer wherein the method includes generating a source beam for the interferometer, therein the source beam included a first input beam at a first frequency and a second input beam at a second frequency that is different from the first frequency, and using the source beam supplied to the

20   interferometer, to make a sequence of measurements of an interference signal for a selected spot on or in the object. The first and second input beams are coextensive and share the same temporal window function. The making of the sequence of measurements involves, for each measurement of the sequence of measurements, introducing a corresponding different shift in a selected parameter of the first input beam and a

25   corresponding different shift in the selected parameter of the second input beam, wherein selected parameter is selected from the group consisting of phase and frequency. Each measurement of the sequence of measurements simultaneously captures information for both conjugated quadratures of fields of reflected, scattered, or transmitted beams from the selected spot.

30   In general, in still yet another aspect, the invention features a method of generating an source beam, that includes generating an output beam that includes a first

beam at a first frequency and a second beam at a second frequency that is different from the first frequency, wherein the first and second beams within the output beam being coextensive; and introducing a sequence of different shifts in a selected parameter of each of the first and second beams, wherein the selected parameter is selected from a group

5   consisting of phase and frequency.

In general, in another aspect, the invention features a method of performing measurements of an object using a scanning confocal interferometer in which there is an array of pinholes. The method includes generating an input beam for the scanning interferometer, wherein the input beam included a first beam at a first frequency and a

10   second beam at a second frequency that is different from the first frequency, and wherein the first and second beams are coextensive and share the same temporal window function. The method also includes causing an image of the array of pinholes to scan across the object so that each pinhole of a conjugate set of pinholes among the array of pinholes becomes conjugate to a selected spot on or in the object at successive times during the

15   scan; for each pinhole of the conjugate set of pinholes, measuring an interference signal value for a selected spot on or in the object, wherein the measured interference signal value for each pinhole of the conjugate set of pinholes simultaneously captures information for two orthogonal components of conjugated quadratures of fields of reflected, scattered, or transmitted beams from the selected spot.

20   In general, in yet another aspect, the invention features a method of performing measurements of an object using a scanning confocal interferometer in which there is an array of pinholes. In this case, the method includes generating an input beam for the scanning interferometer, wherein the input beam included a first beam at a first frequency and a second beam at a second frequency that is different from the first frequency, and

25   wherein the first and second beams are coextensive and share the same temporal window function. The method also includes causing an image of the array of pinholes to scan across the object so that each detector element of a conjugate set of detector elements among an array of detector elements becomes conjugate to a selected spot on or in the object at successive times during the scan; for each detector of the conjugate set of

30   detectors, measuring an interference signal value for a selected spot on or in the object, wherein the measured interference signal value for each detector of the conjugate set of

11

detectors simultaneously captures information for two orthogonal components of conjugated quadratures of fields of reflected, scattered, or transmitted beams from the selected spot.

An advantage of at least one embodiment of the present invention is that a one-dimensional, two-dimensional or three-dimensional image of a substrate may be obtained in interferometric confocal or non-confocal far -field and near -field microscopy when operating in a scanning mode with a relatively fast scan rate. The image comprises a one-dimensional array, a two-dimensional array or a three-dimensional array of conjugated quadratures of reflected and/or scattered or transmitted fields.

Another advantage of at least one embodiment of the present invention is that information used in the determination of a conjugated quadratures of reflected and/or scattered or transmitted fields by a substrate is obtained jointly, *i.e.*, simultaneously.

Another advantage of at least one embodiment of the present invention is that the conjugated quadratures of fields that are obtained jointly when operating in the scanning mode and using either the bi-homodyne or quad-homodyne detection methods have reduced sensitivity to effects of pinhole-to-pinhole variations in the properties of a conjugate set of pinholes used in a confocal microscopy system that are conjugate to a spot in or on the substrate being imaged at different times during the scan.

Another advantage of at least one embodiment of the present invention is that the conjugated quadratures of fields that are obtained jointly when operating in the scanning mode and using either the bi-homodyne or the quad-homodyne detection methods have reduced sensitivity to effects of pixel-to-pixel variation of properties within a set of conjugate pixels that are conjugate to a spot in or on the substrate being imaged at different times during the scan.

Another advantage of at least one embodiment of the present invention is that the conjugated quadratures of fields that are obtained jointly when operating in the scanning mode and using either the bi-homodyne or the quad-homodyne detection methods have reduced sensitivity to effects of pulse to pulse variations of a

12

Atty. Docket No. 114096.121US2
(Client Ref. ZI-47)

respective set of pulses or pulse sequences of the input beam to the interferometer system.

Another advantage of at least one embodiment of the present invention is an increased throughput for an interferometric far -field or near -field confocal or non-
5   confocal microscope with respect to the number of spots in and/or on a substrate imaged per unit time.

Another advantage of at least one embodiment of the present invention is reduced systematic errors in a one-dimensional, a two-dimensional or a three-dimensional image of a substrate obtained in interferometric far -field and near -
10   field confocal and non-confocal microscopy.

Another advantage of at least one embodiment of the present invention is reduced sensitivity to vibrations in generating one-dimensional, two-dimensional or three-dimensional images of a substrate by interferometric far -field and near -field confocal and non-confocal microscopy.

15   Another advantage of at least one embodiment of the present invention is reduced sensitivity to an overlay error of a spot in or on the substrate that is being imaged and a conjugate image of a conjugate pixel of a multi-pixel detector during the acquisition of the four electrical interference values for each spot in and/or on a substrate imaged using interferometric far -field and/or near -field confocal and non-
20   confocal microscopy. Overlay errors are errors in the set of four conjugate images of a respective set of conjugate detector pixels relative to the spot being imaged for either the bi-homodyne quad-homodyne detection methods.

Another advantage of at least one embodiment of the present invention is that the phase of an input beam component does not affect values of measured
25   conjugated quadratures when operating in frequency-shift mode of either the bi-homodyne or quad-homodyne detection methods.

Brief Description of the Drawings

Fig. **1a** is a diagram of an interferometric system that uses the bi-homodyne
30   and quad-homodyne detection methods.

Fig. **1b** is a schematic diagram of a beam-conditioner configured to operate in a two-frequency generator and phase shifter.

Fig. **1c** is a schematic diagram of a beam-conditioner configured to operate in a two-frequency generator and frequency-shifter.

5   Fig. **2a** is a schematic diagram of a confocal microscope system.

Fig. **2b** is a schematic diagram of catadioptric imaging system.

Fig. **2c** is a schematic diagram of a pinhole array used in a confocal microscope system.

10   **Detailed Description**

Apparatus and methods are described herein for joint measurements of conjugated quadratures of fields of reflected and/or scattered and/or transmitted beams in interferometry such as scanning interferometric far-field and near-field confocal and non-confocal microscopy and in interferometric based metrology such

15   as linear displacement interferometers. A bi-homodyne detection method and a quad-homodyne detection method are used to obtain measurements of quantities subsequently used in determination of joint measurements of the conjugated quadratures of fields. The prefixes bi- and quad- refer to the number of different coextensive measurement and corresponding reference beams present in an

20   interferometer system simultaneously, *i.e.*, 2 and 4, respectively.

With respect to information content and signal-to-noise ratios, the conjugated quadratures of fields obtained jointly in a microscopy system that is operating in a scanning mode and using either the bi-homodyne or quad-homodyne detection methods are substantially equivalent to conjugated quadratures of fields obtained

25   when operating the microscopy system in a step and stare mode, *i.e.*, a non-scanning mode. The conjugated quadratures of fields obtained jointly when operating in the scanning mode and using either the bi-homodyne or the quad-homodyne detection methods have reduced sensitivity to pinhole-to-pinhole variations in properties of a conjugate set of pinholes used in a confocal microscopy system and reduced

30   sensitivity to pixel-to-pixel variation of properties within a set of conjugate pixels of a multipixel detector in confocal and non-confocal microscopy systems.

14

The conjugated quadratures of fields obtained jointly when operating in the scanning mode and using either the bi-homodyne or the quad-homodyne detection method have reduced sensitivity to pulse to pulse variations of the input beam used in generating the conjugated quadratures of fields, reduced sensitivity to vibrations

5   of a substrate, and reduced sensitivity to a relative motion of a substrate being imaged during the acquisition of joint measurements of the conjugated quadratures of fields. The reduced sensitivity is relative to conjugated quadratures of fields obtained when operating in a single-homodyne detection mode and for operating in either a scanning or non-scanning mode. In microscopy applications, conjugated

10   quadratures of fields are obtained for each spot in and/or on a substrate that is imaged.

The conjugated quadratures of fields that are obtained jointly in a single or multiple wavelength linear displacement interferometer operating in a scanning mode and using either the bi-homodyne or the quad-homodyne detection methods

15   have a reduced phase redundancy problem and have reduced sensitivity to vibrations as compared to a single or multiple wavelength linear or angular displacement interferometer operating in a scanning mode and using a single-homodyne detection method.

Several embodiments are described that comprise interferometric confocal

20   and non-confocal far -field and near-field microscopy systems and a linear displacement interferometer, e.g., such as used in wavelength monitors, refractivity of gas monitors, monitors of the reciprocal dispersive power Γ of a gas, and dispersion interferometry. In the first embodiment, the difference in the optical path length of a reference beam and a measurement beam in a interferometric far-field

25   confocal microscope is a relatively large non-zero value, e.g., 0.2 m, and in the second embodiment, the difference in the optical path length of the reference beam and the measurement beam in a interferometric confocal far-field microscope is nominally zero. The difference in the optical path length of the reference and measurement beams in interferometric measurements is normally kept a minimum

30   value. However, in certain interferometric far-field confocal microscopes the difference in the optical path length of the reference and measurement beams is a

relatively large value such as described in U.S. Provisional Patent Application No. 60/442,982 [ZI-45] entitled "Interferometric Confocal Microscopy Incorporating Pinhole Array Beam-Splitter" by Henry A. Hill, the contents of which are herein incorporated in their entirety by reference.

5   A general description of embodiments incorporating various aspects of the present invention will first be given wherein the bi-homodyne and the quad-homodyne detection methods are used in interferometer systems for measuring conjugated quadratures of fields of beams reflected and/or scattered and of beams transmitted by a substrate. Referring to Fig. **1a**, an interferometer system is shown

10   diagrammatically comprising an interferometer generally shown as numeral **10** for measuring beams reflected and/or scattered and beams transmitted by a measurement object **60**, a source **18**, a beam-conditioner **22**, detector **70**, and an electronic processor and controller **80**. Source **18** is a pulsed source that generates input beam **20** comprising either one, two, or four frequency components. Beam **20**

15   is incident on and exits beam-conditioner **22** as input beam **24** that has either two or four frequency components. The measurement beam components of the two or four frequency components of input beam **24** are coextensive in space and have the same temporal window function and the corresponding reference beam components are coextensive in space and have the same temporal window function.

20   Reference and measurement beams may be generated in either beam-conditioner **22** from a set of beams or in interferometer **10** for each of the two or four frequency components of input beam **24**. Measurement beam **30A** generated in either beam-conditioner **22** or in interferometer **10** is incident on substrate **60**. Measurement beam **30B** is a return measurement beam generated as either a portion

25   of measurement beam **30A** reflected and/or scattered by substrate **60** or a portion of measurement beam **30A** transmitted by substrate **60**. Return measurement beam **30B** is combined with the reference beam in interferometer **10** to form output beam **32**.

          Output beam **32** is detected by detector **70** to generate either one or two

30   electrical interference signals per source pulse or pulse sequence for the bi-homodyne or quad-homodyne detection methods, respectively, and transmitted as

signal **72**. Detector **70** may comprise an analyzer to select common polarization states of the reference and return measurement beam components of beam **32** to form a mixed beam. Alternatively, interferometer **10** may comprise an analyzer to select common polarization states of the reference and return measurement beam

5   components such that beam **32** is a mixed beam.

In practice, known phase shifts are introduced between the reference and measurement beam components of output beam **32** by two different techniques. In one technique, phase shifts are introduced between the reference and measurement beam components for each of the two or four frequency components of input beam

10   **24** by beam-conditioner **22** as controlled by signal **74** from electronic processor and controller **80**. In the second technique, phase shifts are introduced between corresponding reference and measurement beam components for each of the two or four frequency components of output beam **32** as a consequence of a non-zero optical path difference between the reference and measurement beam paths in

15   interferometer **10** and corresponding frequency shifts introduced to the two or four frequency components of input beam **24** by beam-conditioner **22** and/or source **18** as controlled by signal **74** from electronic processor and controller **80**.

There are different ways to configure source **18** and beam-conditioner **22** to meet the input beam requirements of different embodiments described herein.

20   Reference is made to Fig. **1b** where beam-conditioner **22** is configured as a two-frequency generator and a phase-shifter and source **18** is configured to generate beam **20** with one frequency component. The two-frequency generator and phase-shifter configuration comprises acousto-optic modulators **1020, 1026, 1064** and **1068**; polarizing beam-splitters **1030, 1042, 1044,** and **1056**; phase-shifters **1040**

25   and **1052**; half wave phase retardation plates **1072** and **1074**; non-polarizing beam-splitter **1070**; and mirrors **1036, 1038, 1050,** and **1054**.

Input beam **20** is incident on acousto-optic modulator **1020** with a plane of polarization parallel to the plane of Fig. **1b**. A first portion of beam **20** is diffracted by acousto-optic modulator **1020** as beam **1022** and then by acousto-optic modulator

30   **1026** as beam **1028** having a polarization parallel to the plane of Fig. **1b**. A second portion of beam **20** is transmitted as a non-diffracted beam **1024** having a plane of

polarization parallel to the plane of Fig. **1b**. The acoustic power to acousto-optic modulator **1020** is adjusted such that beams **1022** and **1024** have nominally the same intensity.

5   Acousto-optic modulators **1020** and **1026** may be of either the non-isotropic Bragg diffraction type or of the isotropic Bragg diffraction type. The frequency shifts introduced by acousto-optic modulators **1020** and **1026** are of the same sign and equal to 1/4 of the desired frequency shift between the two frequency components of input beam **24**. Also the direction of propagation of beam **1028** is parallel to the direction of propagation of beam **1024**.

10   Beam **1024** is diffracted by acousto-optic modulators **1064** and **1068** as beam **1082** having a polarization parallel to the plane of Fig. **1b**. Acousto-optic modulators **1064** and **1068** may be of either the non-isotropic Bragg diffraction type or of the isotropic Bragg diffraction type. The frequency shifts introduced by acousto-optic modulators **10640** and **1068** are of the same sign and equal to 1/4 of

15   the desired frequency shift between the two frequency components of input beam **24**. Also the direction of propagation of beam **1082** is parallel to the direction of propagation of beam **1024**.

Beams **1028** and **1082** are incident on half-wave phase retardation plates **1072** and **1074**, respectively, and transmitted as beams **1076** and **1078**, respectively.

20   Half-wave phase retardation plates **1072** and **1074** are oriented such that the planes of polarization of beams **1076** and **1078** are at 45 degrees to the plane of Fig. **1b**. The components of beams **1076** and **1078** polarized parallel to the plane of Fig. **1b** will be used as the measurement beam components in interferometer **10** and the components of beams **1076** and **1078** polarized orthogonal to the plane of Fig. **1b**

25   will be used as the reference beam components in interferometer **10**.

Continuing with reference to Fig. **1b**, beam **1076** is incident on polarizing beam-splitter **1044** and the respective measurement and reference beam components transmitted and reflected, respectively, as beams **1046** and **1048**, respectively. Measurement beam component **1046** is transmitted by polarizing beam-splitter **1056**

30   as a measurement beam component of beam **1058** after reflection by mirror **1054**. Reference beam component **1048** is reflected by polarizing beam-splitter **1056** as

reference beam component of beam **1058** after reflection by mirror **1050** and transmission by phase-shifter **1052**. Beam **1058** is incident on beam-splitter **1070** and a portion thereof is reflected as a component of beam **24**.

Beam **1078** is incident on polarizing beam-splitter **1030** and the respective

5   measurement and reference beam components transmitted and reflected, respectively, as beams **1032** and **1034**, respectively. Measurement beam component **1032** is transmitted by polarizing beam-splitter **1042** as a measurement beam component of beam **1060** after reflection by mirror **1036**. Reference beam component **1034** is reflected by polarizing beam splitter **1042** as reference beam

10   component of beam **1060** after reflection by mirror **1038** and transmission by phase-shifter **1040**. Beam **1060** is incident on beam-splitter **1070** and a portion thereof is transmitted as a component of beam **24** after reflection by mirror **1056**.

Phase-shifters **1052** and **1040** introduce phase shifts between respective reference and measurement beams according to signal **74** from electronic processor

15   and controller **80** (see Fig. **1a**). The schedule of the respective phase shifts is described in the subsequent discussion of Equation (1). Phase-shifters **1052** and **1040** may be for example of the optical-mechanical type comprising for example prisms or mirrors and piezoelectric translators or of the electro-optical modulator type.

20   Beam **24** that exits beam-conditioner **22** comprises one reference beam and measurement beam having one frequency, a second reference beam and measurement beam having a second frequency, and relative phases of the reference beams and the measurement beams that are controlled by electronic processor and controller **80** through control signal **74** .

25   Continuing with a description of different ways to configure source **18** and beam-conditioner **22** to meet the input beam requirements of different embodiments described herein, reference is made to Fig. **1c** where beam-conditioner **22** is configured as a two-frequency generator and a frequency shifter. The two-frequency generator and frequency-shifter configuration comprises acousto-optic

30   modulators **1120**, **1126**, **1130**, **1132**, **1142**, **1146**, **1150**, **1154**, **1058**, and **1062**; beam-splitter **1168**; and mirror **1166**.

Source **18** is configured to generate beam **20** with a single frequency component. Beam **20** is incident on acousto-optic modulator **1120** with a plane of polarization parallel to the plane of Fig. **1c**. A first portion of beam **20** is diffracted by acousto-optic modulator **1120** as beam **1122** and then by acousto-optic modulator

5   **1126** as beam **1128** having a polarization parallel to the plane of Fig. **1c**. A second portion of beam **20** is transmitted as a non-diffracted beam **1124** having a plane of polarization parallel to the plane of Fig. **1c**. The acoustic power to acousto-optic modulator **1120** is adjusted such that beams **1122** and **1124** have nominally the same intensity.

10   Acousto-optic modulators **1120** and **1126** may be of either the non-isotropic Bragg diffraction type or of the isotropic Bragg diffraction type. The frequency shifts introduced by acousto-optic modulators **1120** and **1126** are of the same sign and equal to 1/2 of a frequency shift Δf that will generate in interferometer **10** a relative $\pi/2$ phase shift between a corresponding reference beam and a

15   measurement beam that have a relative change in frequency equal to the frequency shift Δf. The direction of propagation of beam **1128** is parallel to the direction of propagation of beam **1124**.

Continuing with Fig. **1c**, beam **1128** is incident on acousto-optic modulator **1132** and is either diffracted by acousto-optic modulator **1132** as beam **1134** or

20   transmitted by acousto-optic modulator **1132** as beam **1136** according to control signal **74** (see Fig. **1a**) from electronic processor and controller **80**. When beam **1134** is generated, beam **1134** is diffracted by acousto-optic modulators **1142, 1146,** and **1150** as a frequency-shifted beam component of beam **1152**. The frequency shifts introduced by acousto-optic modulators **1132, 1142, 1146,** and **1150** are all in

25   the same direction and equal in magnitude to $\Delta f/2$. Thus the net frequency shift introduced by acousto-optic modulators **1132, 1142, 1146,** and **1150** is $\pm 2\Delta f$ and will generate a relative π phase between the respective reference and measurement beams in interferometer **10**. The net frequency shift introduced by acousto-optic modulators **1120, 1126, 1132, 1142, 1146,** and **1150** is $\Delta f \pm 2\Delta f$ and will generate a

respective relative phase shift of $\pi/2 \pm \pi$ between the respective reference and measurement beams in interferometer **10**.

When beam **1136** is generated, beam **1136** is transmitted by acousto-optic modulator **1150** according to control signal **74** from electronic processor and

5 controller **80** as a non-frequency shifted beam component of beam **1152** with respect to beam **1128**. The net frequency shift introduced by acousto-optic modulators **1120**, **1126**, **1132**, and **1150** is Δf which will generate a respective relative phase shift of $\pi/2$ between the respective reference and measurement beams in interferometer **10**.

10 Beam **1124** is incident on acousto-optic modulator **1130** and is either diffracted by acousto-optic modulator **1130** as beam **1140** or transmitted by acousto-optic modulator **1130** as beam **1138** according to control signal **74** from electronic processor and controller **80**. When beam **1140** is generated, beam **1140** is diffracted by acousto-optic modulators **1154**, **1158**, and **1162** as a frequency-shifted beam

15 component of beam **1164**. The frequency shifts introduced by acousto-optic modulators **1130**, **1154**, **1158**, and **1162** are all in the same direction and equal to $\pm\Delta f/2$. Thus the net frequency shift introduced by acousto-optic modulators **1130**, **1154**, **1158**, and **1162** is $\pm 2\Delta f$ and will generate a relative phase shift of π between the respective reference and measurement beams on transit through interferometer

20 **10**. The net frequency shift introduced by acousto-optic modulators **1120**, **1130**, **1154**, **1158**, and **1162** is $\pm 2\Delta f$ and will generate a respective relative phase shift of $\pm\pi$ between the respective reference and measurement beams on transit through interferometer **10**

When beam **1138** is generated, beam **1138** is transmitted by acousto-optic

25 modulator **1162** according to control signal **74** from electronic processor and controller **80** as a non-frequency shifted beam component of beam **1164**. The frequency shift introduced by acousto-optic modulators **1120**, **1130**, and **1162** is 0 and will generate a respective relative phase shift of 0 between the respective reference and measurement beams on transit through interferometer **10**.

21

Beams **1152** and **1164** may be used directly as input beam **24** when an embodiment requires spatially separated reference and measurement beams for an input beam. When an embodiment requires coextensive reference and measurement beams as an input beam, beam **1152** and **1164** are combined by beam-splitter **1168**

5   to form beam **24**. Acousto-optic modulators **1120, 1126, 1130, 1132, 1142, 1146, 1150, 1154, 1058,** and **1062** may be either of the non-isotropic Bragg diffraction type or of the isotropic Bragg diffraction type. Beams **1152** and **1164** are both polarized in the plane of Fig. 1c for either non-isotropic Bragg diffraction type or of the isotropic Bragg diffraction type and beam-splitter **1168** is of the non-polarizing

10   type.

With a continuation of the description of different ways to configure source **18** and beam-conditioner **22** to meet the input beam requirements of different embodiments, source **18** will preferably comprise a pulse source. There are a number of different ways for producing a pulsed source [see Chapter 11 entitled

15   "Lasers", *Handbook of Optics,* 1, 1995 (McGraw-Hill, New York) by W. Silfvast]. Each pulse of source **18** may comprise a single pulse or a train of pulses such as generated by a mode locked Q-switched Nd:YAG laser. A single pulse train is referenced herein as a pulse sequence and a pulse and a pulse sequence are used herein interchangeably.

20   Source **18** may be configured in certain embodiments to generate two or four frequencies by techniques such as described in a review article entitled "Tunable, Coherent Sources For High-Resolution VUV and XUV Spectroscopy" by B. P. Stoicheff, J. R.Banic, P. Herman, W. Jamroz, P. E. LaRocque, and R. H. Lipson in *Laser Techniques for Extreme Ultraviolet Spectroscopy,* T.J. McIlrath and R.R.

25   Freeman, Eds., (American Institute of Physics) p 19 (1982) and references therein. The techniques include for example second and third harmonic generation and parametric generation such as described in the articles entitled "Generation of Ultraviolet and Vacuum Ultraviolet Radiation" by S. E. Harris, J. F. Young, A. H. Kung, D. M. Bloom, and G. C. Bjorklund in *Laser Spectroscopy I,* R. G. Brewer and

30   A. Mooradi, Eds. (Plenum Press, New York) p 59, (1974) and "Generation of Tunable Picosecond VUV Radiation" by A. H. Kung, *Appl. Phys. Lett.* **25**, p 653

(1974). The contents of the three cited articles are herein incorporated in their entirety by reference.

The output beams from source **18** comprising two or four frequency components may be combined in beam-conditioner **22** by beam-splitters to form

5   coextensive measurement and reference beams that are either spatially separated or coextensive as required in various embodiments. When source **18** is configured to furnish two or four frequency components, the frequency shifting of the various components required in certain embodiments may be introduced in source **18** for example by frequency modulation of input beams to parametric generators and the

10   phase shifting of reference beams relative to measurement beams in beam-conditioner **22** may be achieved by phase shifters of the optical-mechanical type comprising for example prisms or mirrors and piezoelectric translators or of the electro-optical modulator type.

The general description is continued with reference to Fig. **1a**. Input beam

15   **24** is incident on interferometer **10** wherein reference beams and measurement beams are present in input beam **24** or are generated from input beam **24** in interferometer **10**. The reference beams and measurement beams comprise two arrays of reference beams and two arrays of measurement beams wherein the arrays may comprise arrays of one element. The arrays of measurement beams are incident

20   on or focused on and/or in substrate **60** and arrays of return measurement beams are generated by reflection and/or scattering or transmission by the substrate. In the case of single element arrays for the reference beams and measurement beams, the measurement beams are generally reflected or transmitted by substrate **60**. The arrays of reference beams and return measurement beams are combined by a beam-

25   splitter to form two arrays of output beam components. The arrays of output beam components are mixed with respect to state of polarization either in interferometer **10** or in detector **70**. The arrays of output beams are subsequently focused to spots on pixels of a multi-pixel or single pixel detector as required and detected to generate electrical interference signal **72**.

30   The conjugated quadratures of fields of return measurement beams are obtained by making a set of four measurements of the electrical interference signal

72. In single homodyne detection, for each of the four measurements of the

electrical interference signal **72**, a known sequence of phase shifts is introduced

between the reference beam component and the return measurement beam

component of the output beam **32**. A sequence of phase shifts comprise 0, $\pi/4$,

5    $\pi/2$, and $3\pi/2$. For reference, the subsequent data processing procedure used to

extract the conjugated quadratures of the reflected/scattered fields for an input beam

comprising a single frequency component is described for example in U.S. Patent

No. 6,445,453 (ZI-14) entitled "Scanning Interferometric Near-Field Confocal

Microscopy" by Henry A. Hill, the contents of which are incorporated herein in

10   their entirety by reference.

Referring to the bi-homodyne detection method used in various

embodiments, a set of four electrical interference signal values are obtained for each

spot on and/or in substrate **60** being imaged. The set of four electrical interference

signal values S_j, $j = 1,2,3,4$, used for obtaining conjugated quadratures of fields

15   for a single a spot on and/or in a substrate being imaged is represented for the bi-

homodyne detection within a scale factor by the formula

$$S_j = P_j \left\{ \begin{array}{l} \xi_j{}^2 |A_1|^2 + \zeta_j{}^2 |B_1|^2 + \eta_j{}^2 |C_1|^2 + \zeta_j \eta_j 2 |B_1| |C_1| \cos\varphi_{B_1 C_1 \varepsilon_j} \\ + \xi_j \zeta_j 2 |A_1| |B_1| \cos\varphi_{A_1 B_1 \varepsilon_j} + \varepsilon_j \xi_j \eta_j 2 |A_1| |C_1| \cos\varphi_{A_1 C_1} \\ + \xi_j{}^2 |A_2|^2 + \zeta_j{}^2 |B_2|^2 + \eta_j{}^2 |C_2|^2 + \zeta_j \eta_j 2 |B_2| |C_2| \cos\varphi_{B_2 C_2 \gamma_j} \\ + \xi_j \zeta_j 2 |A_2| |B_2| \cos\varphi_{A_2 B_2 \gamma_j} + \gamma_j \xi_j \eta_j 2 |A_2| |C_2| \cos\varphi_{A_2 C_2} \end{array} \right\} \tag{1}$$

20   where coefficients A_1 and A_2 represent the amplitudes of the reference beams

corresponding to the first and second frequency components of the input beam;

coefficients B_1 and B_2 represent the amplitudes of background beams

corresponding to reference beams A_1 and A_2, respectively; coefficients C_1 and C_2

represent the amplitudes of the return measurement beams corresponding to

25   reference beams A_1 and A_2, respectively; P_j represents the integrated intensity of

the first frequency component of the input beam in pulse j of the pulse sequence; and the values for ε_j and γ_j are listed in Table 1. The change in the values of ε_j and γ_j from 1 to -1 or from -1 to 1 correspond to changes in relative phases of respective reference and measurement beams. The coefficients ξ_j, ζ_j, and η_j

5   represent effects of variations in properties of a conjugate set of four pinholes such as size and shape if used in the generation of the spot on and/or in substrate **60** and the sensitivities of a conjugate set of four detector pixels corresponding to the spot on and/or in substrate **60** for the reference beam, the background beam, and the return measurement beam, respectively.

10

Table 1

j	ε_j	γ_j	$\varepsilon_j \gamma_j$
1	1	1	1
2	-1	-1	1
3	-1	1	-1
4	1	-1	-1

15

It is assumed in Equation (1) that the ratio of $\left| A_2 \right| / \left| A_1 \right|$ is not dependent on j or on the value of P_j. In order to simplify the representation of S_j so as to project the important features without departing from either the scope or spirit of the

20   present invention, it is also assumed in Equation (1) that the ratio of the amplitudes of the return measurement beams corresponding to A_2 and A_1 is not dependent on j or on the value of P_j. However, the ratio $\left| C_2 \right| / \left| C_1 \right|$ will be different from the

ratio $|A_2|/|A_1|$ when the ratio of the amplitudes of the measurement beam

components corresponding to A_2 and A_1 are different from the ratio $|A_2|/|A_1|$.

Noting that $\cos\varphi_{A_2C_2} = \pm\sin\varphi_{A_1C_1}$ by the control of the relative phase shifts

between corresponding reference and return measurement beam components in

5   beam **32**, Equation (1) may be rewritten as

$$S_j = P_j \left\{ \begin{array}{l} \xi_j^2\left(|A_1|^2+|A_2|^2\right)+\zeta_j^2\left(|B_1|^2+|B_2|^2\right)+\eta_j^2\left(|C_1|^2+|C_2|^2\right) \\[2mm] +2\xi_j\zeta_j\left(|A_1||B_1|\cos\varphi_{A_1B_1\varepsilon_j}+|A_2||B_2|\cos\varphi_{A_2B_2\gamma_j}\right) \\[2mm] +2\xi_j\eta_j\left[\varepsilon_j|A_1||C_1|\cos\varphi_{A_1C_1}+\gamma_j\left(\dfrac{|A_2|}{|A_1|}\right)\left(\dfrac{|C_2|}{|C_1|}\right)|A_1||C_1|\sin\varphi_{A_1C_1}\right] \\[2mm] +2\zeta_j\eta_j\left(\varepsilon_j|B_1||C_1|\cos\varphi_{B_1C_1\varepsilon_j}+\gamma_j|B_2||C_2|\cos\varphi_{B_2C_2\gamma_j}\right) \end{array} \right\} \quad (2)$$

where the relationship $\cos\varphi_{A_2C_2} = \sin\varphi_{A_1C_1}$ has been used without departing from

10   either the scope or spirit of the present invention.

The change in phase $\varphi_{A_1B_1\varepsilon_j}$ for a change in ε_j and the change in phase $\varphi_{A_2B_2\gamma_j}$

for a change in γ_j may be different from π in embodiments depending on where

and how the background beam is generated. It may be of value in evaluating the

effects of the background beams to note that the factor $\cos\varphi_{B_1C_1\varepsilon_j}$ may be written

15   as $\cos\left[\varphi_{A_1C_1}+\left(\varphi_{B_1C_1\varepsilon_j}-\varphi_{A_1C_1}\right)\right]$ where the phase difference $\left(\varphi_{B_1C_1\varepsilon_j}-\varphi_{A_1C_1}\right)$ is

the same as the phase $\varphi_{A_1B_1\varepsilon_j}$, *i.e.*, $\cos\varphi_{B_1C_1\varepsilon_j}=\cos\left(\varphi_{A_1C_1}+\varphi_{A_1B_1\varepsilon_j}\right)$.

It is evident from inspection of Equation (2) that the term in Equation (2)

corresponding to the component of conjugated quadratures $|C_1|\cos\varphi_{A_1C_1}$ is a

rectangular function that has a mean value of zero and is symmetric about $j=2.5$

20   since ε_j is symmetric about $j=2.5$. In addition the term in Equation (2)

corresponding to the component of conjugated quadratures $|C_1|\sin\varphi_{A_1C_1}$ in Equation

(2) is a rectangular function that has a mean value of zero and is antisymmetric about $j = 2.5$ since γ_j is a antisymmetric function about $j = 2.5$. Another important property by the design of the bi-homodyne detection method is that the conjugated quadratures $|C_1|\cos\varphi_{A_1C_1}$ and $|C_1|\sin\varphi_{A_1C_1}$ terms are orthogonal over the

5   range of $j = 1,2,3,4$ since ε_j and γ_j are orthogonal over the range of $j = 1,2,3,4$,

$$i.e., \sum_{j=1}^{4} \varepsilon_j \gamma_j = 0.$$

Information about conjugated quadratures $|C_1|\cos\varphi_{A_1C_1}$ and $|C_1|\sin\varphi_{A_1C_1}$ are obtained using the symmetric and antisymmetric properties and orthogonality property of the conjugated quadratures terms in Equation (2) as represented by the

10   following digital filters applied to the signal values S_j:

$$F_1(S) = \sum_{j=1}^{4} \varepsilon_j \frac{S_j}{P_j' \xi_j'^2} = \left(|A_1|^2 + |A_2|^2\right) \sum_{j=1}^{4} \varepsilon_j \left(\frac{P_j}{P_j'}\right)\left(\frac{\xi_j^2}{\xi_j'^2}\right)$$

$$+ \left(|B_1|^2 + |B_2|^2\right) \sum_{j=1}^{4} \varepsilon_j \left(\frac{P_j}{P_j'}\right)\left(\frac{\zeta_j^2}{\xi_j'^2}\right) + \left(|C_1|^2 + |C_2|^2\right) \sum_{j=1}^{4} \varepsilon_j \left(\frac{P_j}{P_j'}\right)\left(\frac{\eta_j^2}{\xi_j'^2}\right)$$

$$+ 2|A_1||C_1|\cos\varphi_{A_1 C_1} \sum_{j=1}^{4} \left(\frac{P_j}{P_j'}\right)\left(\frac{\xi_j \eta_j}{\xi_j'^2}\right)$$

$$+ 2\left(\frac{|A_2|}{|A_1|}\right)\left(\frac{|C_2|}{|C_1|}\right)|A_1||C_1|\sin\varphi_{A_1 C_1} \sum_{j=1}^{4} \varepsilon_j \gamma_j \left(\frac{P_j}{P_j'}\right)\left(\frac{\xi_j \eta_j}{\xi_j'^2}\right)$$

$$+ 2|A_1||B_1| \sum_{j=1}^{4} \varepsilon_j \left(\frac{P_j}{P_j'}\right)\left(\frac{\xi_j \zeta_j}{\xi_j'^2}\right)\cos\varphi_{A_1 B_1 \varepsilon_j}$$

$$+ 2|A_2||B_2| \sum_{j=1}^{4} \varepsilon_j \left(\frac{P_j}{P_j'}\right)\left(\frac{\xi_j \zeta_j}{\xi_j'^2}\right)\cos\varphi_{A_2 B_2 \gamma_j}$$

$$+ 2|B_1||C_1| \sum_{j=1}^{4} \left(\frac{P_j}{P_j'}\right)\left(\frac{\zeta_j \eta_j}{\xi_j'^2}\right)\cos\varphi_{B_1 C_1 \varepsilon_j} \tag{3}$$

$$+ 2|B_2||C_2| \sum_{j=1}^{4} \varepsilon_j \gamma_j \left(\frac{P_j}{P_j'}\right)\left(\frac{\zeta_j \eta_j}{\xi_j'^2}\right)\cos\varphi_{B_2 C_2 \gamma_j} ,$$

$$F_2(S) = \sum_{j=1}^{4} \gamma_j \frac{S_j}{P_j' \xi_j'^2} = \left(|A_1|^2 + |A_2|^2\right) \sum_{j=1}^{4} \gamma_j \left(\frac{P_j}{P_j'}\right) \left(\frac{\xi_j^2}{\xi_j'^2}\right)$$

$$+ \left(|B_1|^2 + |B_2|^2\right) \sum_{j=1}^{4} \gamma_j \left(\frac{P_j}{P_j'}\right) \left(\frac{\zeta_j^2}{\xi_j'^2}\right) + \left(|C_1|^2 + |C_2|^2\right) \sum_{j=1}^{4} \gamma_j \left(\frac{P_j}{P_j'}\right) \left(\frac{\eta_j^2}{\xi_j'^2}\right)$$

$$+ 2|A_1||C_1|\cos\varphi_{A_1 C_1} \sum_{j=1}^{4} \varepsilon_j \gamma_j \left(\frac{P_j}{P_j'}\right) \left(\frac{\xi_j \eta_j}{\xi_j'^2}\right)$$

$$+ 2\left(\frac{|A_2|}{|A_1|}\right)\left(\frac{|C_2|}{|C_1|}\right)|A_1||C_1|\sin\varphi_{A_1 C_1} \sum_{j=1}^{4} \left(\frac{P_j}{P_j'}\right) \left(\frac{\xi_j \eta_j}{\xi_j'^2}\right)$$

$$+ 2|A_1||B_1| \sum_{j=1}^{4} \gamma_j \left(\frac{P_j}{P_j'}\right) \left(\frac{\xi_j \zeta_j}{\xi_j'^2}\right) \cos\varphi_{A_1 B_1 \varepsilon_j}$$

$$+ 2|A_2||B_2| \sum_{j=1}^{4} \gamma_j \left(\frac{P_j}{P_j'}\right) \left(\frac{\xi_j \zeta_j}{\xi_j'^2}\right) \cos\varphi_{A_2 B_2 \gamma_j}$$

$$+ 2|B_1||C_1| \sum_{j=1}^{4} \varepsilon_j \gamma_j \left(\frac{P_j}{P_j'}\right) \left(\frac{\zeta_j \eta_j}{\xi_j'^2}\right) \cos\varphi_{B_1 C_1 \varepsilon_j} \tag{4}$$

$$+ 2|B_2||C_2| \sum_{j=1}^{4} \left(\frac{P_j}{P_j'}\right) \left(\frac{\zeta_j \eta_j}{\xi_j'^2}\right) \cos\varphi_{B_2 C_2 \gamma_j}$$

where ξ_j' and P_j' are values used in the digital filters to represent ξ_j and P_j.

The parameter

5

$$\left[\left(\frac{|A_2|}{|A_1|}\right)\left(\frac{|C_2|}{|C_1|}\right)\right] \tag{5}$$

in Equations (3) and (4) needs to be determined in order complete the determination of a conjugated quadratures. The parameter given in Equation (5) can be measured

10   for example by introducing $\pi/2$ phase shifts into the relative phase of the reference

beam and the measurement beam and repeating the measurement for the conjugated quadratures. The ratio of the amplitudes of the conjugated quadratures corresponding to $\left(\sin\varphi_{A_1C_1}/\cos\varphi_{A_1C_1}\right)$ from the first measurement divided by the ratio of the amplitudes of the conjugated quadratures corresponding to

5   $\left(\sin\varphi_{A_1C_1}/\cos\varphi_{A_1C_1}\right)$ from the second measurement is equal to

$$\left[\left(\frac{|A_2|}{|A_1|}\right)\left(\frac{|C_2|}{|C_1|}\right)\right]^2. \tag{6}$$

Note that certain of the factors in Equations (3) and (4) have nominal values

10   of 4 within a scale factor, $e.g.$,

$$\sum_{j=1}^{4}\left(\frac{P_j}{P_j'}\right)\left(\frac{\xi_j\eta_j}{\xi_j'^2}\right)\simeq 4, \quad \sum_{j=1}^{4}\left(\frac{P_j}{P_j'}\right)\left(\frac{\zeta_j\eta_j}{\xi_j'^2}\right)\simeq 4. \tag{7}$$

The scale factors correspond to the average values for the ratios of ξ_j'/η_j and

15   ξ_j'/ζ_j, respectively, assuming that the average value of $P_j/P_j'\cong 1$. Certain other of the factors in Equations (3) and (4) have nominal values of zero, $e.g.$,

$$\sum_{j=1}^{4} \varepsilon_j \left(\frac{P_j}{P_j'}\right)\left(\frac{\xi_j^2}{\xi_j'^2}\right) \simeq 0, \quad \sum_{j=1}^{4} \varepsilon_j \left(\frac{P_j}{P_j'}\right)\left(\frac{\zeta_j^2}{\xi_j'^2}\right) \simeq 0,$$

$$\sum_{j=1}^{4} \varepsilon_j \left(\frac{P_j}{P_j'}\right)\left(\frac{\eta_j^2}{\xi_j'^2}\right) \simeq 0,$$

$$\sum_{j=1}^{4} \gamma_j \left(\frac{P_j}{P_j'}\right)\left(\frac{\xi_j^2}{\xi_j'^2}\right) \simeq 0, \quad \sum_{j=1}^{4} \gamma_j \left(\frac{P_j}{P_j'}\right)\left(\frac{\zeta_j^2}{\xi_j'^2}\right) \simeq 0,$$

$$\sum_{j=1}^{4} \gamma_j \left(\frac{P_j}{P_j'}\right)\left(\frac{\eta_j^2}{\xi_j'^2}\right) \simeq 0,$$

$$\sum_{j=1}^{4} \varepsilon_j \gamma_j \left(\frac{P_j}{P_j'}\right)\left(\frac{\xi_j \eta_j}{\xi_j'^2}\right) \simeq 0.$$

(8)

The remaining factors,

5

$$\sum_{j=1}^{4} \varepsilon_j \left(\frac{P_j}{P_j'}\right)\left(\frac{\xi_j \zeta_j}{\xi_j'^2}\right) \cos\varphi_{A_1 B_1 \varepsilon_j}, \quad \sum_{j=1}^{4} \varepsilon_j \left(\frac{P_j}{P_j'}\right)\left(\frac{\xi_j \zeta_j}{\xi_j'^2}\right) \cos\varphi_{A_2 B_2 \gamma_j},$$

$$\sum_{j=1}^{4} \left(\frac{P_j}{P_j'}\right)\left(\frac{\zeta_j \eta_j}{\xi_j'^2}\right) \cos\varphi_{B_1 C_1 \varepsilon_j}, \quad \sum_{j=1}^{4} \varepsilon_j \gamma_j \left(\frac{P_j}{P_j'}\right)\left(\frac{\zeta_j \eta_j}{\xi_j'^2}\right) \cos\varphi_{B_2 C_2 \gamma_j},$$

(9)

$$\sum_{j=1}^{4} \gamma_j \left(\frac{P_j}{P_j'}\right)\left(\frac{\xi_j \zeta_j}{\xi_j'^2}\right) \cos\varphi_{A_1 B_1 \varepsilon_j}, \quad \sum_{j=1}^{4} \gamma_j \left(\frac{P_j}{P_j'}\right)\left(\frac{\xi_j \zeta_j}{\xi_j'^2}\right) \cos\varphi_{A_2 B_2 \gamma_j},$$

$$\sum_{j=1}^{4} \varepsilon_j \gamma_j \left(\frac{P_j}{P_j'}\right)\left(\frac{\zeta_j \eta_j}{\xi_j'^2}\right) \cos\varphi_{B_1 C_1 \varepsilon_j}, \quad \sum_{j=1}^{4} \left(\frac{P_j}{P_j'}\right)\left(\frac{\zeta_j \eta_j}{\xi_j'^2}\right) \cos\varphi_{B_2 C_2 \gamma_j},$$

will have nominal magnitudes ranging from approximately zero to approximately 4

times a cosine factor and either the average value of factor $\left(P_j/P_j'\right)\left(\xi_j \zeta_j/\xi_j'^2\right)$ or

10     $\left(P_j/P_j'\right)\left(\zeta_j \eta_j/\xi_j'^2\right)$ depending on the properties respective phases. For the portion

31

of the background with phases that do not track to a first approximation the phases of the respective measurement beams, the magnitudes of all of the terms listed in the Equation (9) will be approximately zero. For the portion of the background with phases that do track to a first approximation the phases of the respective

5   measurement beams, the magnitudes of the terms listed in Equation (9) will be approximately 4 times a cosine factor and either the average value of factor

$$\left(P_j/P_j'\right)\left(\xi_j\zeta_j/\xi_j'^2\right) \text{ and or factor } \left(P_j/P_j'\right)\left(\zeta_j\eta_j/\xi_j'^2\right).$$

The two largest terms in Equations (3) and (4) are generally the terms that have the factors $\left(|A_1|^2 + |A_2|^2\right)$ and $\left(|B_1|^2 + |B_2|^2\right)$. However, the corresponding

10   terms are substantially eliminated in various embodiments by selection of ξ_j' values

for the terms that have $\left(|A_1|^2 + |A_2|^2\right)$ as a factor and by the design of ζ_j values for

the terms that have $\left(|B_1|^2 + |B_2|^2\right)$ as a factor as shown in Equation (8).

The largest contribution from effects of background is represented by the contribution to the interference term between the reference beam and the portion of

15   the background beam generated by the measurement beam **30A**. This portion of the effect of the background can be measured by measuring the corresponding conjugated quadratures of the portion of the background with the return measurement beam component of beam **32** set equal to zero, *i.e.*, measuring the respective electrical interference signals S_j with substrate **60** removed and with

20   either $|A_2| = 0$ or $|A_1| = 0$ and visa versa. The measured conjugated quadratures of the portion of the effect of the background can then be used to compensate for the respective background effects beneficially in an end use application if required.

Information about the largest contribution from effects of background amplitude $2\xi_j\zeta_j|A_1||B_1|$ and phase $\varphi_{A_1B_1\varepsilon_j}$, *i.e.*, the interference term between the

25   reference beam and the portion of background beam generated by the measurement beam **30A**, may be obtained by measuring S_j for $j = 1,2,3,4$ as a function of relative phase shift between reference beam and the measurement beam **30A** with

substrate **60** removed and either $|A_2| = 0$ or $|A_1| = 0$ and visa versa and Fourier analyzing the measured values of S_j. Such information can be used to help identify the origin of the respective background.

5 Other techniques may be incorporated into embodiments to reduce and/or compensate for the effects of background beams without departing from either the scope or spirit of the present invention such as described in commonly owned U.S. Patent Nos. 5,760,901 entitled "Method And Apparatus For Confocal Interference Microscopy With Background Amplitude Reduction and Compensation," 5,915,048 entitled "Method and Apparatus for Discrimination In-Focus Images from Out-of-
10 Focus Light Signals from Background and Foreground Light Sources," and 6,480,285 B1 wherein each of three patents are by Henry A. Hill. The contents of each of the three cited patents are herein incorporated in their entirety by reference.

The selection of values for ξ'_j is based on information about coefficients ξ_j for $j = 1,2,3,4$ that may be obtained by measuring the S_j for $j = 1,2,3,4$ with only
15 the reference beam present in the interferometer system. In certain embodiments, this may correspond simply blocking the measurement beam components of input beam **24** and in certain other embodiments, this may correspond to simply measuring the S_j for $j = 1,2,3,4$ with substrate **60** removed. A test of the

correctness of a set of values for ξ'_j is the degree to which the $\left(|A_1|^2 + |A_2|^2 \right)$ terms
20 in Equations (3) and (4) are zero.

Information about coefficients $\xi_j \eta_j$ for $j = 1,2,3,4$ may be obtained by scanning an artifact past the spots corresponding to the respective four conjugate detector pixels with either $|A_2| = 0$ or $|A_1| = 0$ and measuring the conjugated quadratures component $2|A_1||C_1|\cos\varphi_{A_1C_1}$ or $2|A_1||C_1|\sin\varphi_{A_1C_1}$, respectively. A
25 change in the amplitude of the $2|A_1||C_1|\cos\varphi_{A_1C_1}$ or $2|A_1||C_1|\sin\varphi_{A_1C_1}$ term corresponds to a variation in $\xi_j \eta_j$ as a function of j. Information about the

33

coefficients $\xi_j \eta_j$ for $j = 1,2,3,4$ may be used for example to monitor the stability of one or more elements of interferometer system **10**.

The bi-homodyne detection method described herein is a robust technique for the determination of conjugated quadratures of fields. First, the conjugated

5 quadratures $|C_1|\cos\varphi_{A_1C_1}$ and $|C_1|\sin\varphi_{A_1C_1}$ are the primary terms in the digitally filtered values $F_1(S)$ and $F_2(S)$, respectively, as expressed by Equations (3) and (4), respectively, since as noted in the discussion with respect to Equation (8), the terms with the factors $\left(|A_1|^2 + |A_2|^2\right)$ and $\left(|B_1|^2 + |B_2|^2\right)$ are substantially zero.

Secondly, the coefficients of $|C_1|\cos\varphi_{A_1C_1}$ and $|C_2|\sin\varphi_{A_1C_1}$ terms in

10 Equations (3) and (4) are identical. Thus highly accurate measurements of the interference terms between the return measurement beam and the reference beam with respect to amplitudes and phases, $i.e.$, highly accurate measurements of conjugated quadratures of fields can be measured wherein first order variations in ξ_j and first order errors in normalizations such as $\left(P_j/P_j'\right)$ and $\left(\xi_j^2/\xi_j'^2\right)$ enter in

15 only second or higher order. This property translates into a significant advantage. Also, the contributions to each component of the conjugated quadratures $|C_1|\cos\varphi_{A_1C_1}$ and $|C_2|\sin\varphi_{A_1C_1}$ from a respective set of four electrical interference signal values have the same window function and thus are obtained as jointly determined values.

20 Other distinguishing features of the bi-homodyne technique described herein are evident in Equations (3) and (4): the coefficients of the conjugated quadratures $|C_1|\cos\varphi_{A_1C_1}$ and $|C_1|\sin\varphi_{A_1C_1}$ in Equations (3) and (4), respectively, corresponding to the first equation of Equations (7) are identical independent of errors in assumed values for ξ_j'; the coefficients of the conjugated quadratures $|C_1|\sin\varphi_{A_1C_1}$ and

25 $|C_1|\cos\varphi_{A_1C_1}$ in Equations (3) and (4), respectively, corresponding to the fourth equation of Equations (8) are identical independent of errors in assumed values for

34

ξ_j'. Thus highly accurate values of the phases corresponding to conjugated

quadratures can be measured with first order variations in ξ_j and first order errors

in normalizations such as $\left(P_j/P_j'\right)$ and $\left(\xi_j{}^2/\xi_j'{}^2\right)$ enter in only through some high

order effect.

5   It is also evident that since the conjugated quadratures of fields are obtained

jointly when using the bi-homodyne detection method, there is a significant

reduction in the potential for an error in tracking phase as a result of a phase

redundancy unlike the situation possible in single-homodyne detection of

conjugated quadratures of fields.

10   There are a number of advantages of the bi-homodyne detection method

described herein as a consequence of the conjugated quadratures of fields being

jointly acquired quantities. One advantage is a reduced sensitivity the effects of an

overlay error of a spot in or on the substrate that is being imaged and a conjugate

image of conjugate pixel of a multi-pixel detector during the acquisition of four

15   electrical interference signal values of each spot in and/or on a substrate imaged

using interferometric far-field and/or near-field confocal and non-confocal

microscopy. Overlay errors are errors in the set of four conjugate images of a

respective set of conjugate detector pixels relative to the spot being imaged.

Another advantage is that when operating in the scanning mode there is a

20   reduced sensitivity to effects of pinhole-to-pinhole variations in properties of a

conjugate set of pinholes used in a confocal microscopy system that are conjugate to

a spot in or on the substrate being imaged at different times during the scan.

Another advantage is that when operating in the scanning mode there is a

reduced sensitivity to effects of pixel-to-pixel variation of properties within a set of

25   conjugate pixels that are conjugate to a spot in or on the substrate being imaged at

different times during the scan.

Another advantage is that when operating in the scanning mode there is

reduced sensitivity to effects of pulse sequence to pulse sequence variations of a

respective conjugate set of pulse sequences of the input beam **24** to the

30   interferometer system.

The pinholes and pixels of a multi-pixel detector of a set of conjugate pinholes and conjugate pixels of a multi-pixel detector may comprise contiguous pinholes of an array of pinholes and/or contiguous pixels of a multi-pixel detector or may comprise selected pinholes from an array of pinholes and/or pixels from an array of pixels wherein the separation between the selected pinholes is an integer number of pinhole spacings and the separation between an array of respective pixels corresponds to an integer number of pixel spacings without loss of lateral and/or longitudinal resolution and signal-to-noise ratios. The corresponding scan rate would be equal to the integer times the spacing of spots on the measurement object **60** conjugate to set of conjugate pinholes and/or set of conjugate pixels divided by the read out rate of the multi-pixel detector. This property permits a significant increase in throughput for an interferometric far-field or near-field confocal or non-confocal microscope with respect to the number of spots in and/or on a substrate imaged per unit time.

Referring to the quad-homodyne detection method used in various embodiments described herein, a set of four electrical interference signal values are obtained for each spot on and/or in substrate **60** being imaged with two pulse sequences from source **18** and beam-conditioner **22**. The set of four electrical interference signal values S_j, $j = 1,2,3,4$ used for obtaining conjugated quadratures of fields for a single a spot on and/or in a substrate being imaged is represented for the quad-homodyne detection within a scale factor by the formulae

$$S_1 = P_1 \left\{ \begin{array}{l} \xi_1^2 |A_1|^2 + \zeta_1^2 |B_1|^2 + \eta_1^2 |C_1|^2 + \zeta_1 \eta_1 2 |B_1||C_1| \cos\varphi_{B_1 C_1 \varepsilon_1} \\ + \xi_1 \zeta_1 2 |A_1||B_1| \cos\varphi_{A_1 B_1 \varepsilon_1} + \varepsilon_1 \xi_1 \eta_1 2 |A_1||C_1| \cos\varphi_{A_1 C_1} \\ + \xi_1^2 |A_2|^2 + \zeta_1^2 |B_2|^2 + \eta_1^2 |C_2|^2 + \zeta_1 \eta_1 2 |B_2||C_2| \cos\varphi_{B_2 C_2 \gamma_1} \\ + \xi_1 \zeta_1 2 |A_2||B_2| \cos\varphi_{A_2 B_2 \gamma_1} + \gamma_1 \xi_1 \eta_1 2 |A_2||C_2| \cos\varphi_{A_2 C_2} \end{array} \right\}, \qquad (10)$$

36

$$S_2 = P_1 \left\{ \begin{array}{l} \xi_2{}^2|A_3|^2 + \zeta_2{}^2|B_3|^2 + \eta_2{}^2|C_3|^2 + \zeta_2\eta_2 2|B_3||C_3|\cos\varphi_{B_3C_3\varepsilon_2} \\ +\xi_2\zeta_2 2|A_3||B_3|\cos\varphi_{A_3B_3\varepsilon_2} + \varepsilon_2\xi_2\eta_2 2|A_3||C_3|\cos\varphi_{A_3C_3} \\ +\xi_2{}^2|A_4|^2 + \zeta_2{}^2|B_4|^2 + \eta_2{}^2|C_4|^2 + \zeta_2\eta_2 2|B_4||C_4|\cos\varphi_{B_4C_4\gamma_2} \\ +\xi_2\zeta_2 2|A_4||B_4|\cos\varphi_{A_4B_4\gamma_2} + \gamma_2\xi_2\eta_2 2|A_4||C_4|\cos\varphi_{A_4C_4} \end{array} \right\}, \quad (11)$$

$$S_3 = P_2 \left\{ \begin{array}{l} \xi_1{}^2|A_1|^2 + \zeta_1{}^2|B_1|^2 + \eta_1{}^2|C_1|^2 + \zeta_1\eta_1 2|B_1||C_1|\cos\varphi_{B_1C_1\varepsilon_3} \\ +\xi_1\zeta_1 2|A_1||B_1|\cos\varphi_{A_1B_1\varepsilon_3} + \varepsilon_3\xi_1\eta_1 2|A_1||C_1|\cos\varphi_{A_1C_1} \\ +\xi_1{}^2|A_2|^2 + \zeta_1{}^2|B_2|^2 + \eta_1{}^2|C_2|^2 + \zeta_1\eta_1 2|B_2||C_2|\cos\varphi_{B_2C_2\gamma_3} \\ +\xi_1\zeta_1 2|A_2||B_2|\cos\varphi_{A_2B_2\gamma_3} + \gamma_3\xi_1\eta_1 2|A_2||C_2|\cos\varphi_{A_2C_2} \end{array} \right\}, \quad (12)$$

$$S_4 = P_2 \left\{ \begin{array}{l} \xi_2{}^2|A_3|^2 + \zeta_2{}^2|B_3|^2 + \eta_2{}^2|C_3|^2 + \zeta_2\eta_2 2|B_3||C_3|\cos\varphi_{B_3C_3\varepsilon_4} \\ +\xi_2\zeta_2 2|A_3||B_3|\cos\varphi_{A_3B_3\varepsilon_4} + \varepsilon_4\xi_2\eta_2 2|A_3||C_3|\cos\varphi_{A_3C_3} \\ +\xi_2{}^2|A_4|^2 + \zeta_2{}^2|B_4|^2 + \eta_2{}^2|C_4|^2 + \zeta_2\eta_2 2|B_4||C_4|\cos\varphi_{B_4C_4\gamma_4} \\ +\xi_2\zeta_2 2|A_4||B_4|\cos\varphi_{A_4B_4\gamma_4} + \gamma_4\xi_2\eta_2 2|A_4||C_4|\cos\varphi_{A_4C_4} \end{array} \right\}, \quad (13)$$

where coefficients A_1, A_2, A_3, and A_4 represent the amplitudes of the reference beams corresponding to the first, second, third, and fourth frequency components, respectively, of input beam **24**; coefficients B_1, B_2, B_3, and B_4 represent the amplitudes of background beams corresponding to reference beams A_1, A_2, A_3, and A_4, respectively; coefficients C_1, C_2, C_3, and C_4 represent the amplitudes of the return measurement beams corresponding to reference beams A_1, A_2, A_3, and A_4, respectively; P_1 and P_2 represent the integrated intensities of the first frequency component in the first and second pulse sequences, respectively, of the input beam **24**; and the values for ε_j and γ_j are listed in Table 1. The description of the coefficients ξ_j, ζ_j, and η_j for the quad-homodyne detection method is the same as

37

the corresponding portion of the description given for ξ_j, ζ_j, and η_j of the bi-homodyne detection method.

It is assumed in Equations (10), (11), (12), and (13) that the ratios of $|A_2|/|A_1|$ and $|A_4|/|A_3|$ are not dependent on j or the value of P_j. In order to

5   simplify the representation of S_j so as to project the important features without departing from either the scope or spirit of the present invention, it is also assumed in Equations (10), (11), (12), and (13) that the ratios of the amplitudes of the return measurement beams corresponding to $|A_2|/|A_1|$ and $|A_4|/|A_3|$ are not dependent on j or the value of P_j. However, the ratios $|C_2|/|C_1|$ and $|C_4|/|C_3|$ will be different

10   from the ratios $|A_2|/|A_1|$ and $|A_4|/|A_3|$, respectively, when the ratio of the amplitudes of the measurement beam components corresponding to $|A_2|/|A_1|$ and $|A_4|/|A_3|$, respectively, are different from the ratios $|A_2|/|A_1|$ and $|A_4|/|A_3|$, respectively.

Noting that $\cos\varphi_{A_2 C_2} = \pm\sin\varphi_{A_1 C_1}$ by the control of the relative phase shifts between corresponding reference and measurement beam components in beam **32**,

15   Equations (10), (11), (12), and (13) may be written, respectively, as

$$S_1 = P_1 \left\{ \begin{array}{l} \xi_1^2 \left(|A_1|^2 + |A_2|^2 \right) + \zeta_1^2 \left(|B_1|^2 + |B_2|^2 \right) + \eta_1^2 \left(|C_1|^2 + |C_2|^2 \right) \\[2mm] + 2\zeta_1\eta_1 \left[|B_1||C_1|\cos\varphi_{B_1 C_1 \varepsilon_1} + |B_2||C_2|\cos\varphi_{B_2 C_2 \gamma_1} \right] \\[2mm] + 2\xi_1\eta_1 \left[\varepsilon_1 |A_1||C_1|\cos\varphi_{A_1 C_1} + \gamma_1 \left(\frac{|A_2|}{|A_1|} \right)\left(\frac{|C_2|}{|C_1|} \right)|A_1||C_1|\sin\varphi_{A_1 C_1} \right] \\[2mm] + 2\xi_1\zeta_1 \left[|A_1||B_1|\cos\varphi_{A_1 B_1 \varepsilon_1} + |A_2||B_2|\cos\varphi_{A_2 B_2 \gamma_1} \right] \end{array} \right\}, \quad (14)$$

38

$$S_2 = P_1 \left\{ \begin{array}{l} \xi_2{}^2\left(|A_3|^2 + |A_4|^2\right) + \zeta_2{}^2\left(|B_3|^2 + |B_4|^2\right) + \eta_2{}^2\left(|C_3|^2 + |C_4|^2\right) \\[4pt] + 2\zeta_2\eta_2\left[|B_3||C_3|\cos\varphi_{B_3C_3\varepsilon_2} + |B_4||C_4|\cos\varphi_{B_4C_4\gamma_2}\right] \\[4pt] + 2\xi_2\eta_2\left(\dfrac{|A_3|}{|A_1|}\right)\left(\dfrac{|C_3|}{|C_1|}\right)\left[\begin{array}{l}\varepsilon_2|A_1||C_1|\cos\varphi_{A_1C_1} \\[4pt] + \gamma_2\left(\dfrac{|A_4|}{|A_3|}\right)\left(\dfrac{|C_4|}{|C_3|}\right)|A_1||C_1|\sin\varphi_{A_1C_1}\end{array}\right] \\[4pt] + 2\xi_2\zeta_2\left[|A_3||B_3|\cos\varphi_{A_3B_3\varepsilon_2} + |A_4||B_4|\cos\varphi_{A_4B_4\gamma_2}\right] \end{array} \right\}, \quad (15)$$

$$S_3 = P_2 \left\{ \begin{array}{l} \xi_1{}^2\left(|A_1|^2 + |A_2|^2\right) + \zeta_1{}^2\left(|B_1|^2 + |B_2|^2\right) + \eta_1{}^2\left(|C_1|^2 + |C_2|^2\right) \\[4pt] + 2\zeta_1\eta_1\left[|B_1||C_1|\cos\varphi_{B_1C_1\varepsilon_3} + |B_2||C_2|\cos\varphi_{B_2C_2\gamma_3}\right] \\[4pt] + 2\xi_1\eta_1\left[\varepsilon_3|A_1||C_1|\cos\varphi_{A_1C_1} + \gamma_3\left(\dfrac{|A_2|}{|A_1|}\right)\left(\dfrac{|C_2|}{|C_1|}\right)|A_1||C_1|\sin\varphi_{A_1C_1}\right] \\[4pt] + 2\xi_1\zeta_1\left[|A_1||B_1|\cos\varphi_{A_1B_1\varepsilon_3} + |A_2||B_2|\cos\varphi_{A_2B_2\gamma_3}\right] \end{array} \right\}, \quad (16)$$

5

$$S_4 = P_2 \left\{ \begin{array}{l} \xi_2{}^2\left(|A_3|^2 + |A_4|^2\right) + \zeta_2{}^2\left(|B_3|^2 + |B_4|^2\right) + \eta_2{}^2\left(|C_3|^2 + |C_4|^2\right) \\[4pt] + 2\zeta_2\eta_2\left[|B_3||C_3|\cos\varphi_{B_3C_3\varepsilon_4} + |B_4||C_4|\cos\varphi_{B_4C_4\gamma_4}\right] \\[4pt] + 2\xi_2\eta_2\left(\dfrac{|A_3|}{|A_1|}\right)\left(\dfrac{|C_3|}{|C_1|}\right)\left[\begin{array}{l}\varepsilon_4|A_1||C_1|\cos\varphi_{A_1C_1} \\[4pt] + \gamma_4\left(\dfrac{|A_4|}{|A_3|}\right)\left(\dfrac{|C_4|}{|C_3|}\right)|A_1||C_1|\sin\varphi_{A_1C_1}\end{array}\right] \\[4pt] + 2\xi_2\zeta_2\left[|A_3||B_3|\cos\varphi_{A_3B_3\varepsilon_4} + |A_4||B_4|\cos\varphi_{A_4B_4\gamma_4}\right] \end{array} \right\}, \quad (17)$$

where the relationship $\cos\varphi_{A_2C_2} = \sin\varphi_{A_1C_1}$ has been used without departing from either the scope or spirit of the present invention.

Information about the conjugated quadratures $|C_1|\cos\varphi_{A_1C_1}$ and $|C_1|\sin\varphi_{A_1C_1}$

10 are obtained using the symmetric and antisymmetric properties and orthogonality property of the conjugated quadratures as represented by the following digital filters applied to the signal values S_j:

$$F_3(S) = \left(\frac{1}{P_1'}\right)\left(\frac{S_1}{\xi_1'^2} - \frac{S_2}{\xi_2'^2}\right) - \left(\frac{1}{P_2'}\right)\left(\frac{S_3}{\xi_1'^2} - \frac{S_4}{\xi_2'^2}\right),$$ (18)

$$F_4(S) = \left(\frac{1}{P_1'}\right)\left(\frac{S_1}{\xi_1'^2} - \frac{S_2}{\xi_2'^2}\right) + \left(\frac{1}{P_2'}\right)\left(\frac{S_3}{\xi_1'^2} - \frac{S_4}{\xi_2'^2}\right).$$ (19)

5   The description of ξ_j' and P_j' for the quad-homodyne detection method is the same

as the corresponding description given for ξ_j' and P_j' in the bi-homodyne detection

method. Using Equations (14), (15) (16), (17), (18), and (19), the following

expressions are obtained for the filtered quantities containing components of the

conjugated quadratures $|C_1|\cos\varphi_{A_1 C_1}$ and $|C_1|\sin\varphi_{A_1 C_1}$:

10

$$
\begin{aligned}
F_3(S) = {} & \left(\frac{P_1}{P_1'} - \frac{P_2}{P_2'}\right)\left[\left(|A_1|^2 + |A_2|^2\right)\left(\frac{\xi_1^{\,2}}{\xi_1'^{\,2}}\right) - \left(|A_3|^2 + |A_4|^2\right)\left(\frac{\xi_2^{\,2}}{\xi_2'^{\,2}}\right)\right] \\
& + \left(\frac{P_1}{P_1'} - \frac{P_2}{P_2'}\right)\left[\left(|B_1|^2 + |B_2|^2\right)\left(\frac{\zeta_1^{\,2}}{\xi_1'^{\,2}}\right) - \left(|B_3|^2 + |B_4|^2\right)\left(\frac{\zeta_2^{\,2}}{\xi_2'^{\,2}}\right)\right] \\
& + \left(\frac{P_1}{P_1'} - \frac{P_2}{P_2'}\right)\left[\left(|C_1|^2 + |C_2|^2\right)\left(\frac{\eta_1^{\,2}}{\xi_1'^{\,2}}\right) - \left(|C_3|^2 + |C_4|^2\right)\left(\frac{\eta_2^{\,2}}{\xi_2'^{\,2}}\right)\right] \\
& + 2\left(\frac{P_1}{P_1'} + \frac{P_2}{P_2'}\right)\left[\left(\frac{\xi_1\eta_1}{\xi_1'^{\,2}}\right) + \left(\frac{\xi_2\eta_2}{\xi_2'^{\,2}}\right)\left(\frac{|A_3|}{|A_1|}\right)\left(\frac{|C_3|}{|C_1|}\right)\right]|A_1||C_1|\cos\varphi_{A_1 C_1} \\
& + 2\left(\frac{P_1}{P_1'} - \frac{P_2}{P_2'}\right)\left(\frac{|A_2|}{|A_1|}\right)\left(\frac{|C_2|}{|C_1|}\right)\left[\begin{array}{l}\left(\dfrac{\xi_1\eta_1}{\xi_1'^{\,2}}\right) \\ + \left(\dfrac{\xi_2\eta_2}{\xi_2'^{\,2}}\right)\left(\dfrac{|A_4|}{|A_2|}\right)\left(\dfrac{|C_4|}{|C_2|}\right)\end{array}\right]|A_1||C_1|\sin\varphi_{A_1 C_1} \\
& + 2\left(\frac{P_1}{P_1'}\cos\varphi_{A_1 B_1 \varepsilon_1} - \frac{P_2}{P_2'}\cos\varphi_{A_1 B_1 \varepsilon_3}\right)\frac{\xi_1\zeta_1}{\xi_1'^{\,2}}|A_1||B_1| \\
& - 2\left(\frac{P_1}{P_1'}\cos\varphi_{A_3 B_3 \varepsilon_2} - \frac{P_2}{P_2'}\cos\varphi_{A_3 B_3 \varepsilon_4}\right)\frac{\xi_2\zeta_2}{\xi_2'^{\,2}}|A_3||B_3| \\
& + 2\left(\frac{P_1}{P_1'}\cos\varphi_{A_2 B_2 \gamma_1} - \frac{P_2}{P_2'}\cos\varphi_{A_2 B_2 \gamma_3}\right)\frac{\xi_1\zeta_1}{\xi_1'^{\,2}}|A_2||B_2| \\
& - 2\left(\frac{P_1}{P_1'}\cos\varphi_{A_4 B_4 \gamma_2} - \frac{P_2}{P_2'}\cos\varphi_{A_4 B_4 \gamma_4}\right)\frac{\xi_2\zeta_2}{\xi_2'^{\,2}}|A_4||B_4| \\
& + 2\left(\frac{P_1}{P_1'}\cos\varphi_{B_1 C_1 \varepsilon_1} - \frac{P_2}{P_2'}\cos\varphi_{B_1 C_1 \varepsilon_3}\right)\frac{\xi_1\zeta_1}{\xi_1'^{\,2}}|B_1||C_1| \\
& - 2\left(\frac{P_1}{P_1'}\cos\varphi_{B_3 C_3 \varepsilon_2} - \frac{P_2}{P_2'}\cos\varphi_{B_3 C_3 \varepsilon_4}\right)\frac{\xi_2\zeta_2}{\xi_2'^{\,2}}|B_3||C_3| \\
& + 2\left(\frac{P_1}{P_1'}\cos\varphi_{B_2 C_2 \gamma_1} - \frac{P_2}{P_2'}\cos\varphi_{B_2 C_2 \gamma_3}\right)\frac{\xi_1\zeta_1}{\xi_1'^{\,2}}|B_2||C_2| \\
& - 2\left(\frac{P_1}{P_1'}\cos\varphi_{B_4 C_4 \gamma_2} - \frac{P_2}{P_2'}\cos\varphi_{B_4 C_4 \gamma_4}\right)\frac{\xi_2\zeta_2}{\xi_2'^{\,2}}|B_4||C_4|,
\end{aligned}
$$

$$F_4(S) = \left(\frac{P_1}{P_1'} + \frac{P_2}{P_2'}\right)\left[\left(|A_1|^2 + |A_2|^2\right)\left(\frac{\xi_1^2}{\xi_1'^2}\right) - \left(|A_3|^2 + |A_4|^2\right)\left(\frac{\xi_2^2}{\xi_2'^2}\right)\right]$$

$$+ \left(\frac{P_1}{P_1'} + \frac{P_2}{P_2'}\right)\left[\left(|B_1|^2 + |B_2|^2\right)\left(\frac{\zeta_1^2}{\xi_1'^2}\right) - \left(|B_3|^2 + |B_4|^2\right)\left(\frac{\zeta_2^2}{\xi_2'^2}\right)\right]$$

$$+ \left(\frac{P_1}{P_1'} + \frac{P_2}{P_2'}\right)\left[\left(|C_1|^2 + |C_2|^2\right)\left(\frac{\eta_1^2}{\xi_1'^2}\right) - \left(|C_3|^2 + |C_4|^2\right)\left(\frac{\eta_2^2}{\xi_2'^2}\right)\right]$$

$$+ 2\left(\frac{P_1}{P_1'} - \frac{P_2}{P_2'}\right)\left[\left(\frac{\xi_1\eta_1}{\xi_1'^2}\right) + \left(\frac{\xi_2\eta_2}{\xi_2'^2}\right)\left(\frac{|A_3|}{|A_1|}\right)\left(\frac{|C_3|}{|C_1|}\right)\right]|A_1||C_1|\cos\varphi_{A_1C_1}$$

$$+ 2\left(\frac{P_1}{P_1'} + \frac{P_2}{P_2'}\right)\left(\frac{|A_2|}{|A_1|}\right)\left(\frac{|C_2|}{|C_1|}\right)\left[\begin{array}{l}\left(\frac{\xi_1\eta_1}{\xi_1'^2}\right) \\ + \left(\frac{\xi_2\eta_2}{\xi_2'^2}\right)\left(\frac{|A_4|}{|A_2|}\right)\left(\frac{|C_4|}{|C_2|}\right)\end{array}\right]|A_1||C_1|\sin\varphi_{A_1C_1}$$

$$+ 2\left(\frac{P_1}{P_1'}\cos\varphi_{A_1B_1\varepsilon_1} + \frac{P_2}{P_2'}\cos\varphi_{A_1B_1\varepsilon_3}\right)\frac{\xi_1\zeta_1}{\xi_1'^2}|A_1||B_1|$$

$$- 2\left(\frac{P_1}{P_1'}\cos\varphi_{A_3B_3\varepsilon_2} + \frac{P_2}{P_2'}\cos\varphi_{A_3B_3\varepsilon_4}\right)\frac{\xi_2\zeta_2}{\xi_2'^2}|A_3||B_3|$$

$$+ 2\left(\frac{P_1}{P_1'}\cos\varphi_{A_2B_2\gamma_1} + \frac{P_2}{P_2'}\cos\varphi_{A_2B_2\gamma_3}\right)\frac{\xi_1\zeta_1}{\xi_1'^2}|A_2||B_2|$$

$$- 2\left(\frac{P_1}{P_1'}\cos\varphi_{A_4B_4\gamma_2} + \frac{P_2}{P_2'}\cos\varphi_{A_4B_4\gamma_4}\right)\frac{\xi_2\zeta_2}{\xi_2'^2}|A_4||B_4|$$

$$+ 2\left(\frac{P_1}{P_1'}\cos\varphi_{B_1C_1\varepsilon_1} + \frac{P_2}{P_2'}\cos\varphi_{B_1C_1\varepsilon_3}\right)\frac{\xi_1\zeta_1}{\xi_1'^2}|B_1||C_1|$$

$$- 2\left(\frac{P_1}{P_1'}\cos\varphi_{B_3C_3\varepsilon_2} + \frac{P_2}{P_2'}\cos\varphi_{B_3C_3\varepsilon_4}\right)\frac{\xi_2\zeta_2}{\xi_2'^2}|B_3||C_3|$$

$$+ 2\left(\frac{P_1}{P_1'}\cos\varphi_{B_2C_2\gamma_1} + \frac{P_2}{P_2'}\cos\varphi_{B_2C_2\gamma_3}\right)\frac{\xi_1\zeta_1}{\xi_1'^2}|B_2||C_2|$$

$$- 2\left(\frac{P_1}{P_1'}\cos\varphi_{B_4C_4\gamma_2} + \frac{P_2}{P_2'}\cos\varphi_{B_4C_4\gamma_4}\right)\frac{\xi_2\zeta_2}{\xi_2'^2}|B_4||C_4|. \tag{20}$$

The parameters

$$\left[\left(\frac{|A_2|}{|A_1|} \right) \left(\frac{|C_2|}{|C_1|} \right) \right], \tag{21}$$

$$\left(\frac{|A_4|}{|A_2|} \right) \left(\frac{|C_4|}{|C_2|} \right), \tag{22}$$

$$\left[\left(\frac{|A_3|}{|A_1|} \right) \left(\frac{|C_3|}{|C_1|} \right) \right] \tag{23}$$

need to be determined in order to complete the determination of a conjugated quadratures for certain end use applications. The parameters given by Equations (21), (22), and (23) can for example be measured by procedures analogous to the procedure described for the bi-homodyne detection method with respect to measuring the quantity specified by Equation (5).

The remaining description of the quad-homodyne detection method is the same as corresponding portion of the description given for the bi-homodyne detection method.

It is also evident that since the conjugated quadratures of fields are obtained jointly when using the quad-homodyne detection, there is a significant reduction in the potential for an error in tracking phase as a result of a phase redundancy unlike the situation possible in single-homodyne detection of conjugated quadratures of fields.

There are a number of advantages of the quad-homodyne detection described herein as a consequence of the conjugated quadratures of fields being jointly acquired quantities.

One advantage of the quad-homodyne detection method in relation to the bi-homodyne detection method is a factor of two increase in throughput.

Another advantage is a reduced sensitivity the effects of an overlay error of a spot in or on the substrate that is being imaged and a conjugate image of a pixel of a

43

conjugate set of pixels of a multipixel detector during the acquisition of the four

electrical interference signal values of each spot in and/or on a substrate imaged

using interferometric far-field and/or near-field confocal microscopy. Overlay

errors are errors in the set of four conjugate images of a respective set of conjugate

5   detector pixels relative to the spot being imaged.

Another advantage is that when operating in the scanning mode there is

reduced sensitivity to effects of pulse to pulse variations of a respective conjugate

set of pulses of the input beam 24 to the interferometer system.

Another advantage is that when operating in the scanning mode there is an

10   increase in throughput since only one pulse of the source is required to generate the

four electrical interference values.

A first embodiment is shown schematically in Fig. 2a. The first embodiment

comprises a first imaging system generally indicated as numeral 110, pinhole beam-

splitter 112, detector 170, and a second imaging system generally indicated as numeral

15   210. The second imaging system 210 is low power microscope having a large working

distance, e.g. Nikon ELWD and SLWD objectives and Olympus LWD, ULWD, and

ELWD objectives. The first imaging system 110 comprises the interferometric confocal

microscopy system described in cited commonly owned U.S. Provisional Application No.

60/442,982 (ZI-45).

20   The first imaging system 110 is shown schematically in Fig. 2b. The

imaging system 110 is a catadioptric system such as described in commonly owned

U.S. Patent No. 6,552,852 B1 (ZI-38) entitled "Catoptric and Catadioptric Imaging

System" and U.S. Patent Application No. 10/366,651 filed February 3, 2003 (ZI-43)

and entitled "Catoptric and Catadioptric Imaging System" for which the patent and

25   patent application are by Henry A. Hill and the contents of the patent and patent

application are incorporated herein in their entirety by reference.

Catadioptric imaging system 110 comprises catadioptric elements 140 and 144,

beam splitter 148, and convex lens 150. Surfaces 142A and 146A are convex spherical

surfaces with nominally the same radii of curvature and the respective centers of

30   curvature of surfaces 142A and 146A are conjugate points with respect to beam splitter

148. Surfaces 142B and 146B are concave spherical surfaces with nominally the same

radii of curvature. The centers of curvature of surfaces **142B** and **146B** are the same as

the centers of curvature of surfaces **146A** and **142A**, respectively. The center of

curvature of convex lens **150** is the same as the center of curvature of surfaces **142B** and

146A. The radius of curvature of surface **146B** is selected so as to minimize the loss in

5   efficiency of the imaging system **110** and to produce a working distance for imaging

system **110** acceptable for an end use application. The radius of curvature of convex lens

150 is selected so that the off-axis aberrations of the catadioptric imaging system **110** are

compensated. The medium of elements **140** and **144** may be for example fused silica or

commercially available glass such as SF11. The medium of convex lens **150** may be for

10   example fused silica, YAG, or commercially available glass such as SF11. An important

consideration in the selection of the medium of elements **140** and **144** and convex lens

150 will the transmission properties for the frequencies of beam **124**.

Convex lens **152** has a center of curvature the same as the center of curvature of

convex lens **150**. Convex lenses **150** and **152** are bonded together with pinhole beam-

15   splitter **112** in between. Pinhole array beam-splitter **112** is shown in Fig. **2c**. The pattern

of pinholes in pinhole array beam-splitter is chosen to match the requirements of an end

use application. An example of a pattern is a two dimensional array of equally spaced

pinholes in two orthogonal directions. The pinholes may comprise circular apertures,

rectangular apertures, or combinations thereof such as described in commonly owned

20   U.S. Patent Application No. 09/917,402 filed July 27, 2001 (ZI-15) and entitled

"Multiple-Source Arrays for Confocal and Near-field Microscopy" by Henry A. Hill and

Kyle Ferrio. The contents of the cited patent application are incorporated herein in its

entirety by reference. The spacing between pinholes of pinhole array beam-splitter **112** is

shown in Fig. **2c** as *b* with aperture size *a*.

25   Input beam **124** is reflected by mirror **154** to pinhole beam-splitter **112** where a

first portion thereof is transmitted as reference beam components of output beam **130A**

and **130B** and a second portion thereof scattered as measurement beam components of

beams **126A** and **126B**. The measurement beam components **126A** and **126B** are imaged

as components of beams **128A** and **128B** to an array of image spots in an image plane

30   close to substrate **160**. A portion of the components of beams **128A** and **128B** incident

on substrate **160** are reflected and/or scattered as return measurement beam components

of beams **128A** and **128B**. Return measurement beam components of beams **128A** and **128B** are imaged by catadioptric imaging system **110** to spots that are coincident with the pinholes of pinhole beam-splitter **112** and a portion thereof is transmitted as return measurement beam components of output beams **130A** and **130B**.

5   The description of the imaging properties of catadioptric imaging system **110** is the same as the corresponding portion of the description given for the imaging properties of catadioptric imaging system **10** in cited U.S. Provisional Application No. 60/442,982 (ZI-45) and U.S. Patent Application filed Jan. 27, 2004 entitled "Interferometric Confocal Microscopy Incorporating Pinhole Array Beam-Splitter".

10   The next step is the imaging of output beams **130A** and **130B** by imaging system **210** to an array of spots that coincide with the pixels of a multi-pixel detector such as a CCD to generate an array of electrical interference signals **172**. The array of electrical interference signals is transmitted to signal processor and controller **180** for subsequent processing.

15   The description of input beam **124** is the same as corresponding portions of the description given for input beam **24** of Fig. **1a** with beam-conditioner **122** configured as a two frequency generator and frequency-shifter shown in Fig. **1c**. Input beam **124** comprises two components that have different frequencies and have the same state of plane polarization. The frequency of each component of input

20   beam **124** are shifted between two different preselected frequency values by beam-conditioner **122** according to control signal **174** generated by electronic processor and controller **180**. Source **118** of beam **120** to beam-conditioner **122**, such as a laser, can be any of a variety of single frequency lasers.

        The conjugated quadratures of fields of the return measurement beams are

25   obtained using the bi-homodyne detection as described in the description of Figs. **1a-1c** wherein sets of four measurements of the electrical interference signals **172** are made. For each of the set of four measurements of the electrical interference signals **172**, a known sequence of phase shifts is introduced between the reference beam component and the return measurement beam component of output beams

30   **130A** and **130B**.

The sequence of phase shifts is generated in the first embodiment by shifting the frequencies of components of input beam **124** by beam-conditioner **122**. There is a difference in optical path length between the reference beam components and the return beam components of output beams **130A** and **130B** and as a consequence,

5 a change in frequencies of components of input beam **124** will generate corresponding phase shifts between the reference beam components and the return beam components of output beams **130A** and **130B**. For an optical path difference L between the reference beam components and the return beam components of output beams **130A** and **130B**, there will be for a frequency shift Δf a

10 corresponding phase shift φ where

$$\varphi = 2\pi L \left(\frac{\Delta f}{c} \right) \tag{24}$$

and c is the free space speed of light. Note that L is not a physical path length

15 difference and depends for example on the average index of refraction of the measurement beam and the return measurement beam paths. For an example of a phase shift $\varphi = \pi/2$ and a value of $L = 0.25$ m, the corresponding frequency shift $\Delta f = 300$ MHz.

Referring to the quad-homodyne detection method used in various

20 embodiments, a set of four electrical interference signals are obtained for each spot on and/or in substrate **60** being imaged.

Two different modes are described for the acquisition of the electrical interference signals **172**. The first mode to be described is a step and stare mode wherein substrate **160** is stepped between fixed locations corresponding to locations

25 where image information is desired. The second mode is a scanning mode. In the step and stare mode for generating a one-dimensional, a two-dimensional or a three-dimensional profile of substrate **160**, substrate **160** mounted in wafer chuck **184**/stage **190** is translated by stage **190**. The position of stage **190** is controlled by transducer **182** according to servo control signal **178** from electronic processor and

30 controller **180**. The position of stage **190** is measured by metrology system **188** and

position information acquired by metrology system **188** is transmitted to electronic processor and controller **180** to generate an error signal for use in the position control of stage **190**. Metrology system **188** may comprise for example linear displacement and angular displacement interferometers and cap gauges.

5 Electronic processor and controller **180** translates wafer stage **190** to a desired position and then acquires a set of four electrical interference signal values corresponding. After the acquisition of the sequence of four electrical interference signals, electronic processor and controller **180** then repeats the procedure for the next desired position of stage **190**. The elevation and angular orientation of

10 substrate **160** is controlled by transducers **186A** and **186B**.

The second mode for the acquisition of the electrical interference signal values is next described wherein the electrical interference signal values are obtained with the position of stage **190** scanned in one or more directions. In the scanning mode, source **118** is pulsed at times controlled by signal **192** from signal

15 processor and controller **180**. Source **118** is pulsed at times corresponding to the registration of the conjugate image of pinholes of pinhole array beam-splitter **112** with positions on and/or in substrate **160** for which image information is desired.

There will be a restriction on the duration or "pulse width" of a beam pulse sequence τ_{p1} produced by source **120** as a result of the continuous scanning mode

20 used in the third variant of the first embodiment. Pulse width τ_{p1} will be a parameter that in part controls the limiting value for spatial resolution in the direction of a scan to a lower bound of

$$\tau_{p1}v \ , \tag{25}$$

25

where v is the scan speed. For example, with a value of $\tau_{p1} = 50$ nsec and a scan speed of $v = 0.20$ m/sec, the limiting value of the spatial resolution $\tau_{p1}v$ in the direction of scan will be

$$\tau_{p1} v = 10 \text{ nm}. \tag{26}$$

Pulse width τ_{p1} will also determine the minimum frequency difference that can be used in the bi-homodyne detection. In order that there be no contributions to

5   the electrical interference signals from interference between fields of conjugated quadratures, the minimum frequency spacing Δf_{min} is expressed as

$$\Delta f_{min} \gg \frac{1}{\tau_{p1}}. \tag{27}$$

10   For the example of $\tau_{p1} = 50 \text{ nsec}$, $1/\tau_{p1} = 20 \text{ MHz}$.

The frequencies of input beam **124** are controlled by signal **174** from signal processor and controller **180** to correspond to the frequencies that will yield the desired phase shifts between the reference and return measurement beam components of output beams **130A** and **130B**. In the first mode for the acquisition

15   of the electrical interference signals **172**, the set of four electrical interference signals corresponding to a set of four electrical interference values are generated by common pixels of detector **170**. In the second mode for the acquisition of electrical interference signals **172**, a set of four electrical interference signal values are not generated by a common pixel of detector **170**. Thus in the second mode of

20   acquisition, the differences in pixel efficiency and the differences in sizes of pinholes in pinhole array beam-splitter **112** are compensated in the signal processing by signal processor and controller **180** as described in the description of the bi-homodyne detection given with respect to Figs. **1a-1c**. The joint measurements of conjugated quadratures of fields are generated by electric processor and controller

25   **180** as previously described in the description of the bi-homodyne detection method.

A second embodiment comprises the interferometer system of Figs. **1a-1c** with interferometer **10** comprising an interferometric far-field confocal microscope such as described in cited U.S. Patent No. 5,760,901. In the second embodiment, beam-conditioner **22** is configured as the two frequency generator and phase-shifter

49

shown in Fig. **1b**. Embodiments in cited U.S. Patent No. 5,760,901 are configured to operate in either the reflection or transmission mode. The second embodiment has reduced effects of background because of background reduction features of cited U.S. Patent No. 5,760,901.

5   A third embodiment comprises the interferometer system of Figs. **1a-1c** with interferometer **10** comprising an interferometric far-field confocal microscope such as described in cited U.S. Patent No. 5,760,901 wherein the phase masks are removed. In the third embodiment, beam-conditioner **22** is configured as the two frequency generator and phase-shifter shown in Fig. **1b**. . Embodiments in cited

10   U.S. Patent No. 5,760,901 are configured to operate in either the reflection or transmission mode. The third embodiment with the phase masks of embodiments of cited removed U.S. Patent No. 5,760,901 represent applications of confocal techniques in a basic form.

          A fourth embodiment comprises the interferometer system of Figs. **1a-1c**

15   with interferometer **10** comprising an interferometric far-field confocal microscope such as described in cited U.S. Patent No. 6,480,285 B1. In the fourth embodiment, beam-conditioner **22** is configured as the two-frequency generator and phase-shifter shown in Fig. **1b**. Embodiments in cited U.S. Patent No. 6,480,285 B1 are configured to operate in either the reflection or transmission mode. The fourth

20   embodiment has reduced effects of background because of background reduction features of cited U.S. Patent No. 6,4980,285 B1.

          A fifth embodiment comprises the interferometer system of Figs. **1a-1c** with interferometer **10** comprising an interferometric far-field confocal microscope such as described in cited U.S. Patent No. 6,480,285 B1 wherein the phase masks are

25   removed. In the fifth embodiment, beam-conditioner **22** is configured as the two-frequency generator and phase-shifter shown in Fig. **1b**. Embodiments in cited U.S. Patent No. 6,480,285 B1 are configured to operate in either the reflection or transmission mode. The fifth embodiment with the phase masks of embodiments of cited removed U.S. Patent No. 6,480,285 B1 represent applications of confocal

30   techniques in a basic form.

A sixth embodiment comprises the interferometer system of Figs. **1a-1c** with interferometer **10** comprising an interferometric near-field confocal microscope such as described in U.S. Patent No. 6,445,453 entitled "Scanning Interferometric Near-Field Confocal Microscopy" by Henry A. Hill, the contents of which are

5   herein incorporated in their entirety by reference. In the sixth embodiment, beam-conditioner **22** is configured as the two-frequency generator and phase-shifter shown in Fig. **1b**. Embodiments in cited U.S. Patent No. 6,445,453 are configured to operate in either the reflection or transmission mode. The fifth embodiment of cited U.S. Patent No. 6,445,453 in particular is configured to operate in the

10   transmission mode with the measurement beam separated from the reference beam and incident on the substrate being imaged by a non-confocal imaging system, *i.e.*, the measurement beam at the substrate is not an image of an array of pinholes but an extended spot. Accordingly, the corresponding embodiments of the sixth embodiment represent an application of bi-homodyne detection method in a non-

15   confocal configuration for the measurement beam.

Interferometer **10** may comprise an interferometric apparatus such as described in U.S. Patent No. 4,685,803 entitled "Method And Apparatus For The Measurement Of The Refractive Index Of A Gas" or U.S. Patent No. 4,733,967 entitled "Apparatus Of The Measurement Of The Refractive Index Of A Gas"

20   configured for bi-homodyne detection. Both of the cited patents are by Gary E. Sommargren and the contents of both cited patents are herein incorporated in their entirety by way of reference. Embodiments which comprise interferometric apparatus such as described in the two cited U.S. patents represents configurations of a non-confocal type.

25   Interferometer **10** may comprise a Γ monitor such as described in U.S. Patent No. 6,124,931 entitled "Apparatus And Methods For Measuring Intrinsic Optical Properties Of A Gas" by Henry A. Hill, the contents of which are here within incorporated in their entirety by way of reference. For embodiments which comprise interferometric apparatus such as described in the cited U.S. patent, the

30   described Γ monitor is configured for bi-homodyne detection and the embodiments represent configurations that are of a non-confocal type.

Interferometer **10** may comprise a wavelength monitor such as described in U.S. Patent Provisional Application No. 60/337,459 entitled "A Method For Compensation For Effects Of Non-Isotropic Gas Mixtures In Single-Wavelength And Multiple-Wavelength Dispersion Interferometry" [Z-384, Z-339] by Henry A.

5   Hill, the contents of which are here within incorporated in their entirety by way of reference. For embodiments which comprise interferometric apparatus such as described in the cited U.S. patent, the wavelength monitor is configured for bi-homodyne detection and the embodiments represent configurations that are of a non-confocal type.

10   Interferometer **10** may further comprise any type of interferometer, *e.g.*, a differential plane mirror interferometer, a double-pass interferometer, a Michelson-type interferometer and/or a similar device such as is described in an article entitled "Differential Interferometer Arrangements For Distance And Angle Measurements: Principles, Advantages And Applications" by C. Zanoni, *VDI Berichte* Nr. **749**, 93-

15   106 (1989) configured for bi-homodyne detection. Interferometer **10** may also comprise a passive zero shear plane mirror interferometer as described in U.S. Patent Application Serial No. 10/207,314 entitled "Passive Zero Shear Interferometers" or an interferometer with a dynamic beam steering element such as described in U.S. Patent Application with Serial No. 09/852,369 entitled "Apparatus

20   And Method For Interferometric Measurements Of Angular Orientation And Distance To A Plane Mirror Object" and U.S. Patent 6,271,923 entitled "Interferometry System Having A Dynamic Beam Steering Assembly For Measuring Angle And Distance," all of which are by Henry A. Hill. For embodiments which comprise interferometric apparatus such as described in the cited U.S. patents and

25   the article by Zanoni, the described interferometers are configured for bi-homodyne detection and the embodiments represent configurations that are of a non-confocal type. The contents of the article by Zanoni and the three cited patents by Hill are herein incorporated in their entirety by reference. The interferometer can be designed to monitor, for example, changes in optical path length, changes in

30   physical path length, changes in wavelength of a beam, or changes in direction of propagation of a beam.

Interferometer **10** may further comprise a dispersion interferometer such as described in U.S. Patent No. 6,219,144 B1 entitled "Apparatus and Method for Measuring the Refractive Index and Optical Path Length Effects of Air Using Multiple-Pass Interferometry" by Henry A. Hill, Peter de Groot, and Frank C.

5 Demarest and U.S. Patent No. 6,407,816 entitled "Interferometer And Method For Measuring The Refractive Index And Optical Path Length Effects Of Air" by Peter de Groot, Henry A. Hill, and Frank C. Demarest. The contents of both of the cited patents are herein incorporated in their entirety by reference. For embodiments which comprise interferometric apparatus such as described in the cited U.S.

10 patents, the described interferometers are configured for bi-homodyne detection and the embodiments represent configurations that are of a non-confocal type.

Other embodiments may use the quad-homodyne detection method instead of the bi-homodyne detection method as variants of the embodiments. For the embodiments that are based on the apparatus shown in Figs. **1a-1c**, the

15 corresponding variants of the embodiments that use the quad-homodyne detection method use variants of the apparatus shown in Figs. **1a-1c**. In the variants of the apparatus such as used in the first embodiment, microscope **220** is modified to include a dispersive element such as a direct vision prism and/or a dichroic beam-splitter. When configured with a dichroic beam-splitter, a second detector is further

20 added to the system. Descriptions of the variants of the apparatus are the same as corresponding portions of descriptions given for corresponding systems in cited U.S. Provisional Application No. 60/442,982 [ZI-45]. Corresponding variants of apparatus are used for embodiments that comprise interferometers such as linear displacement interferometers.

25